INVESTIGATION OF THE CHARACTERISTICS OF THE DIRECT CURRENT GLOW DISCHARGE UNDER THE INFLUENCE OF PRESSURE AND VELOCITY UP TO THE SPEED OF SOUND

by

FRANCIS X. [illegible]

Lieutenant Commander, U. S. Navy

July [illegible], 194[illegible]

A Thesis submitted to the Faculty of the Graduate School, University of Minnesota, in partial fulfillment of the requirements for the Degree of Master of Science.

TABLE OF CONTENTS

Table of Contents (con't.)

SUMMARY

This study was conducted to determine the feasibility of using a direct current glow discharge as a velocity meter up to the speed of sound. The primary problem was to show the dependence of the glow discharge characteristics on velocity as separable from the many variables that effect the characteristics. It was confirmed that by using an asymmetrical arrangement of material and form, the previously experienced burning of the electrodes could be successfully avoided. The discharge proved to be both pressure and velocity sensitive and as such adapts itself to use as a pressure probe or velocity meter. However, since the glow is insensitive to temperature, it cannot be utilized as a Machmeter. Unfortunately the results above 740 ft./sec. (Mach number = 0.70) in this report cannot be relied upon but it is expected that with adequate equipment, reliable data up to and beyond the speed of sound can be obtained. The characteristics proved also to be a function of the electrode materials, size, spacing, polarity, and possibly wire length. A .001 inch diameter platinum wire proved to be too small and flexible for velocity measurements whereas the .003 inch wire proved satisfactory.

INTRODUCTION

Although in all probability more papers have been published on various aspects of the glow discharge than on all the other electrical discharge phenomena, it is only in the last few years that attention has been brought to its possibilities as a pressure, velocity, or Mach meter. There is a great need at present for a good instrument that can record accurately the pressure, velocity or Mach number not only in the laboratory but also in the field, such as in an aircraft. In the latter category, an accurate instrument does not exist today as all present instruments are subject to position errors (errors due to the position of the probe with respect to the line of flight and the attitude of the aircraft), instrument errors, losses in the tubes and lines, temperature, and compressibility errors. Then too, air speed indicator readings of the present day must be corrected for altitude (pressure, density change) and temperature if the true air speed is desired. Thus, today a pilot may be flying at 18000 ft. indicating 315 kts. while in reality his true air speed may be in the vicinity of 400 kts., a marked difference very essential to navigation, flight planning and gasoline consumption. It is towards a solution of this problem that this investigation was made to find out if an instrument based on the glow discharge characteristics would be feasible. To the author's knowledge, there is no such instrument available or in

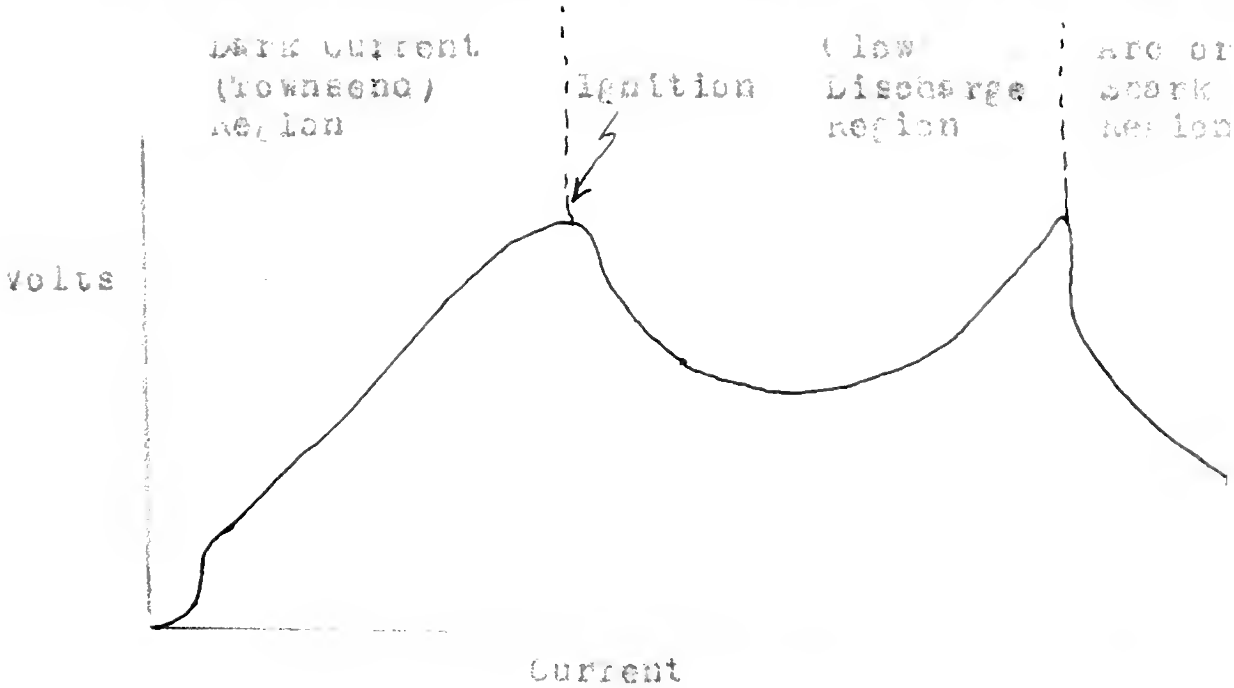
existence that measures flow up to the velocity of sound based on this principle. The prime purpose of the study shall deal with the glow discharge characteristics for a point in dry air as dependent on pressure and Mach number when using different size platinum wires, changing electrode spacing, and changing the polarity of the wire from negative to positive. This study was not intended to be a final quantitative solution of the problem but only an exploratory study of the major parameters affecting the application of the glow discharge for a pressure, velocity or Mach meter.

This study was carried out at the University of Minnesota's Research Center, Rosemount, Minnesota under the supervision of advisor, Professor J. D. Akerman, Head of the Department of Aeronautical Engineering of the University of Minnesota. A debt of appreciation is also owed to Lieutenant Commander Robert A. Bollenberger, a fellow student, Mr. Frank Werner, scientist at the Center, and Professor W. Braithwaite, for their help in construction and alleviation of many of the troubles encountered during the experiments.

THEORY AND PREVIOUS EXPERIMENTS

As is known there are in general three types of electrical discharges in air that have marked significance and different characteristics, namely, the Townsend Discharge or dark current discharge, the glow discharge

and the arc or spark discharge. Of these the first is the only one that gives off no light. The following sketch indicates roughly the characteristics of these discharges.



Dark Current Region

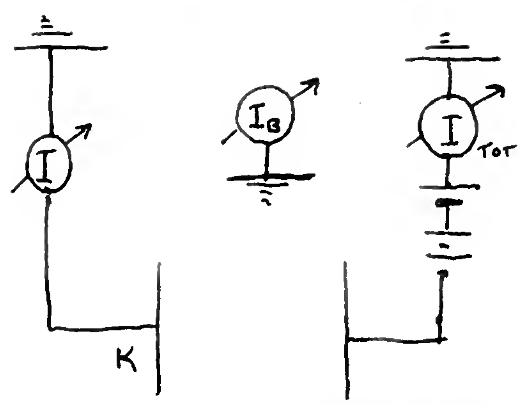
Prior to ignition, a current can be made to flow between two electrodes (the so-called dark current discharge or Townsend Discharge) in air but it is essential that there be an external current in considering the magnitude of this dark current. Charge carriers (positive ions) can be generated externally in the discharge region from such sources as X-rays, ultraviolet light or elevated temperatures as from flames, and these ions will drift to the cathode. If a voltage differential exists across the electrodes, electrons will be attracted towards the anode. These electrons in air at atmospheric pressure have a mean free path of approximately $7.5 \times 10^{-}$[illegible] cm. and due to the impressed voltage, they will fall freely through this distance, striking the gas molecules with

the energy gained in the fall. This kinetic energy is then available for excitation, ionization or dissociation. If the energy is insufficient to produce an inelastic collision, the electrons rebound in an almost perfectly elastic recoil and carry the energy gained into the next free path. Thus the electrons can accumulate energy (thereby raising their temperature). During this accumulation of energy, therefore, no new electrons are formed and the current cannot rise despite the increase in voltage. The initial electrons are eventually transported to the anode with the ions going to the cathode.

When enough energy is accumulated, an electron in traveling to the anode ionizes a neutral molecule by colliding with it and one shell electron is separated. Both electrons now available after the first ionization travel towards the anode and ionize anew. After the next ionization there are then four electrons and three ions, the continuation of this process being known as Townsend's Electron and Ion Avalanche. Although depending on the original current for excitation and magnitude, the process is now self-sustaining but the current is very small being of the order of 10^{-8} to 10^{-10} amperes.

The feasibility of this type current as a velocity meter was successfully investigated by Wilhelm Fucks in 1942. He found that the effect of the air flow consisted in weakening the current by that amount blown away from the electrode gap while the ions move from the

anode to the cathode. The seeming dilemma of having two currents of different magnitudes flowing in one circuit (same voltage with and without velocity) is solved simply by using a circuit as follows:



$I_{tot} = I_b + I_o$

I_{tot} = total current

I_b = current blown away which somehow goes to ground

I_o = current in still air

He discovered that by changing the shape of the electrodes the ion velocities are changed and thereby the characteristics of the apparatus will change when subjected to impressed air flow due to the time the ions are exposed to it. When the shape of the electrode was changed from a point to a sphere, even down to a diameter of 1 mm. (.0396 in.), no decrease in current was established at velocities up to 125 m./sec. thereby indicating that a point or a sphere of extremely small diameter is necessary, at least at subsonic speeds. Fucks also showed that the ignition current (beginning of the glow discharge) increased with increasing flow velocities. This is very significant for the present study as it indicates the glow discharge to be velocity sensitive. The working range of the instrument proved to be a function of the distance between electrodes. Changing the spacing between electrodes changes the characteristic (1) due to a large anode-cathode

path and (2) a reduced ion velocity due to a reduced field intensity in the vicinity of the anode. The smaller the distance the higher the velocity needed to distinguish it from still air characteristics. Its upper limit was defined by ignition and a vertical tangent to the characteristics curve. Again if the anode and cathode are of the same size no velocity response was noticed. The sensitivity, however, proved to be very good for constant voltage (large changes in amperage at various velocities) but poor for constant amperage. As expected there was no burning away of the electrodes.

When there are two electrodes of different sizes and well separated, the field is concentrated at the electrodes and the mechanisms which are active center in the region of the intense field. As the voltage is raised above the dark current region, the fields become sufficiently high for breakdown in these regions long before a spark can propagate across the gas space. This breakdown occurs in two steps, one, at the electrode or electrodes, and secondly, a breakdown of the gap itself; i.e. a spark. The manifestation of breakdown at the electrode is the emission of light, generally called corona or glow discharge.

Glow Discharge Region

Thus as the field strength is raised above the Townsend Discharge region, sufficient energy is accumulated

by the ions to dislodge an electron from the cathode on impact. These new electrons have collisions on their way to the anode and cause another avalanche of ions and electrons. At first there are not enough of these secondary ions to make the process self-sustaining and while there are pulses of corona, they are quickly extinguished (in the order of 10^{-7} to 10^{-2} sec.). This is due to the rapid decline of the field as one moves away from the cathode and also because the electrons in moving away leave behind relatively immobile positive ions whose positive space charge reduces the field (electron's velocity is 500 times that of an ion in atmospheric air). This space charge then is cleared by being swept into the cathode and the current declines. When the field has been increased sufficiently by the removal of positive ions, the last ions start new electron avalanches and the process repeats, the current increasing as the field increases. This region of non self-sustaining corona is known as the Geiger counter regime and has been utilized in atomic work to detect electrons, cosmic ray, gamma or beta ray ionization (Ref. 3 pg. 481-505). In this region the current is increasing and when sufficient secondary ions are formed, (in the vicinity of 1.0 to 1.5 microamps) a steady visible glow is observed and the process becomes self-sustaining as electrons are continuously being displaced from the cathode. The current now increases rapidly, being of the order of 100 to 1000

times dark current magnitude. The color of the glow is dependent of composition of the gas and in the case of air is either salmon pink or lavender. It is this discharge that is to be studied in this report. At atmospheric pressures with the wire point of negative polarity, the glow is localized over a small area but as the pressure is reduced and there is a high diffusion of electrons, the glow becomes very luminous and diffuse over the surface of the electrodes. With the wire of positive polarity at atmospheric pressure the luminosity sometimes spreads as a thin film over the high field portions of the conductor, while at reduced pressure it may extend into the gap somewhat in the form of streamers or striations.

In the previous description of the glow discharge phenomena, the needle has been assumed of negative polarity. When the needle is positive, the discharge, while still a glow, is of a different nature. Ionization takes place at the needle point as before but the positive ions in traveling to the cathode find the field too low for the secondary emission of more electrons. However, ionization from photoelectric emission and ultraviolet radiation from the cathode takes place, the necessary light coming from the glow at the anode and the discharge is again self-sustaining.

While much has been done to establish the characteristics of the glow discharge as a function of

pressure, almost all of it has dealt with pressures of 20 mm. Hg. or less as used in gaseous tubes. Pressure in these regions has a marked effect as would be expected from the low density of the gas, diffusion of electrons, and the increased mean free path. Very little has been done in the region between atmospheric (760 mm. Hg.) and 20 mm. Hg., a region highly important if the glow discharge is to be used in wind tunnels and the earth's atmosphere. Werner has shown (Ref. 2) that pressure has a profound effect on the position of the characteristic curves and includes several characteristics in the desired range. He clearly shows furthermore, that these characteristics shift appreciable due to humidity and wire size, and change somewhat due to plate radius, polarity and electrode spacing. Thus it can be seen that the present study shall have to include a pressure survey for the particular apparatus and the changes in wire size, polarity and spacing. Since dry air is to be used at all times, the variable, humidity, need not be considered.

As stated in the discourse dealing with dark current, velocity is expected to have an effect on the characteristics due to the blowing away of some of the charge carriers, resulting in a loss of current for a given voltage.

The suitability of the glow discharge for velocity dependence was investigated firstly by R. C. Lindvall. According to Lindvall the glow discharge in air

at atmospheric pressure was supposed to be suitable also for investigation of the smaller turbulence of flow with the burning away of the electrodes the only disturbing factor. O. Meier, of the German Aeronautical Research Institute, attempting to check Lindvall's work could obtain no good results for oscillation measurements, primarily due to the burning away of the electrodes, heating up of the electrodes and sudden changes into other discharge forms. However, as pointed out by Werner, Lindvall's needles were relatively large (.15 cm. in diameter), the axis of his points were perpendicular to the airstream and it is possible that he was working with an arc instead of a glow. Werner's preliminary investigation indicated the glow to be sensitive to air stream up to 411 ft./sec. W. Fucks, in investigating the burning away of the electrodes in a glow discharge anemometer, showed that the burning away is essentially due to a contraction of the discharge at the anode (hot spot) and that avoiding the burning away amounts to avoiding the hot spot. This could be done by introducing asymmetry of form or material (or both) into the electrodes, or more simply, by using alternating current of high frequency. Fucks and Schumacher investigated the latter possibility, using platinum electrodes of .5 (.0198") and .3 mm. (.0118") because of their pre-eminence in resistance to oxidation, and found the alternating current glow discharge anemometer to have a working range of only 50 m./sec. (164 ft./sec.)

but yet had more reproducibility than any previous flow instrument.

Consequently the main emphasis of this investigation is to continue Werner's experiment and it is hoped that by using a platinum wire and another material as electrodes, both of different shape, and of the smallness used by Werner, the burning away may be avoided and velocity sensitivity up to the speed of sound may be recorded.

EQUIPMENT AND METHODS

Before describing the equipment and methods in conducting the experiments, it must be borne in mind that this study was carried on jointly with another individual seeking similar information for operations at supersonic instead of subsonic speeds. Consequently the equipment was designed to accomodate and test the effect of both types of flow on the glow discharge.

The wind tunnel used to obtain the required air flow was designed specifically for supersonic speeds in the order of M = 3.0 with the intention of making all subsonic runs either in front of the throat, in the throat itself or, to a limited degree, aft of the throat. In this manner it was believed that results close to M = 1.0 could be attained, and also, the same Mach number could be had at various pressures, showing thereby, any change in the effect of Mach number at different pressures. The air supply was obtained by tapping into the Rosemount Research Laboratories' Hypersonic Tunnel's high pressure tank with a one inch pipe line. This huge tank (1750 cubic feet) holds air at 125 psi gage, and if desired, the large compressor used to pump up this reservoir, could be used simultaneously when testing. With the wind tunnel used in this experiment, it was possible to operate continuously up to the maximum Mach number attained utilizing the compressor, and for an indefinitely long period subsonically without using the compressor. The air supplied

was dry, having a dew point in the order of -40° F. and was dried before storage by an electrodryer.

The arrangement of the wind tunnel is as seen in Fig. 1. The air coming from the storage tank enters by the one inch pipe as shown supported on the extreme left. It then proceeds into an expansion valve to a pipe two inches in diameter and thence into the control valve. This expansion was necessary supersonically to avoid having the actual throat appear in the valve as was the case with a one inch high pressure globe type valve. With the valve open, the air then travels past a union joint into the stagnation chamber, a section of three six inch steel pipes, a total of forty-one (41) inches long. Twenty inches down this chamber in the center of the channel was installed a total head tube of 1/16 inch brass tubing. Ref. Fig. 2, Section A-A. This pressure tap was then led through 3/8 inch steel pipe to a pressure gage, or for finer measurements, and as used in connection with this report, by rubber tubing to a multiple manometer where this stagnation pressure was read in inches of mercury. Thirty-five inches down this stagnation chamber the flow was converted from that in a circular cross-section of six inch diameter to a rectangular cross-section, two by one inches, by means of a hydrostone mold, six inches long. This mold was cast in the pipe with hydrostone by means of a wooden plug cut to the required dimensions on a lathe. Sealing in all the above named sections was accomplished by

the use of hard composition gaskets and Permatex #2 gasket paste.

Following the flow converter was the nozzle block, cut from plexiglass, the design of which appears in Fig. 3. This nozzle was secured to the stagnation chamber by means of eight half inch bolts with the heads countersunk in the end adapter plate. Sealing was made by the use of 1/8 inch rubber padding between the end plate and the plexiglass pulled tightly by means of the holding bolts. The throat dimensions of the nozzle were 0.250 x 2.00 inches and the nozzle was of the wedge type with a slight rounding at the throat and had a downstream divergence half-angle of four degrees (4^0). It was designed according to the Method of Characteristics by Busemann and the reader is referred to the report by [illegible] Hollenberger, Ref. 10, as to the supersonic flow characteristics of the nozzle. Subsonically, in the vicinity of the throat, the flow appeared satisfactory as evidenced by a very steady manometer up to a Mach number of approximately .85 or .90. Above this, slight fluctuations of the mercury was noticed indicating unsteady conditions and possibly erroneous pressure readings.

The probes, Fig. 4, used to measure the static pressure in the nozzle and to insert the platinum wire electrode into the flow parallel to the static tube (used also as the positive electrode or plate), offered difficulty in construction. The original static probe was a slender

hypodermic steel needle silver soldered to a 1/16 inch brass tube 1/2 inch long, which in turn was silver soldered to a 1/4 inch brass tube about 12 inches long. This proved unsatisfactory as the needle was not steady when subjected to air flow, and finally snapped off at supersonic speeds. The eventual solution was to use a 1/16 inch brass tube one inch long as the static probe with the static orifice eight diameters back from the point. This was then silver soldered to a 3/8 inch steel tube about fifteen inches long. Similar steel construction was necessary for the platinum wire holder to avoid unsteadiness. Eventually it consisted of the platinum wire 1/32 inch long soldered to a steel needle point ground from solid stock steel 3/32 inch in diameter and about 1 1/2 inches long, followed by a half inch piece of 1/4 inch brass tube and approximately fifteen inches of 3/8 inch steel tube. This slow increase in thickness was made in order to avoid any possible disturbance of the flow near the point. As there was to be as much as 10,000 volts of electricity across these probes, all surfaces except the platinum wire and the 1/16" tube of the static probe were then coated with a plastic insulator, Acryloid, to a thickness of 1/16 to 1/8 inch. These probes were fastened eight inches back from the probe tips in Plexiglass holders which, in turn, were secured to a wooden support.

The support (Fig. 4) was a seven inch piece of 2 x 4 inch wood cut to a wedge shaped leading edge and

mounted by screws to a 4 x 4 x 1/4 inch steel plate. This plate with two 1/4 inch bolts as guides, fitted on a steel track twenty-four inches long and it could be secured in any desired position by tightening the bolts. This arrangement, then, allowed the movement of the probes forward and aft to any desired distance down the middle of the tunnel. Spacing of the electrodes apart was accomplished by merely relocating the platinum wire probe holder into the desired set of specially located holes in the wooden support.

In order to obtain the glow discharge at the tip of the platinum wire it was necessary that a voltage supply and a means of measuring the current flow be available. From the work of previous experimentors, a voltage supply of 10,000 volts was deemed ample as was the ability to measure amperage from zero (0) up to 500 microamperes. Since the effect of changing needle polarity was to be investigated, two similar electrical arrangements were made, differing only in the polarity. The circuit diagrams appear in Figs. 5, 6, and 7 and a picture of the control panel appears in Fig. 1.

Essentially, the power supply circuit consisted of a Variac to control the line voltage to the power supply which, in turn, was able to deliver up to 10,000 volts direct current. In this circuit two switches were installed, one to the filament and another for the high voltage side of the power supply to be used only after the filament had been allowed sufficient time to heat up. There were

two such power supplies.

From the output terminals of the power supplies two similar circuits were originated, differing only in polarity (Fig. 6 and 7), circuit one being used to test a positive platinum wire and circuit two to test a negative wire. A voltmeter with a three-way switch incorporating various resistances was installed across the line to vary the voltage as desired and also a microammeter with a three-way switch with various resistance to allow measuring current on three different range scales 0 - 50, 0 - 150, and 0 -500 microamperes. To protect the microammeter a neon tube was put into the circuit and to limit the current through the voltmeter a two megohms resistor and a 1/200 ampere fuse was placed in the line. However, this latter was found inadequate as no fuse could be obtained with high enough voltage rating. Consequently it became necessary to increase the resistance to four megohms and use no fuse, thus limiting the current to the maximum allowable. All resistors were measured to two decimal places by means of a Wheatstone bridge resistor box and the voltmeter calibrated accordingly.

From the large resistors across the line, it became necessary to use extra heavy co-axial cable (line and ground terminals in single casing) to handle the high voltage. This cable was then led to the probes, the high voltage line going to the plate or static tube and the shield or ground connection to the wire probe. Thus, since

the circuits were reversed in polarity, attaching one cable as above gave a negative wire while the other, a positive wire. To insure against leakage, all high voltage lines were well separated, all connections made very secure, any sharp corners were smoothed round and the probes were insulated heavily with Acryloid.

In order to obtain pressure measurements, (Mach number of zero) for dry air, the glass jar containing a moisture absorbing chemical in the left of Fig. 4 was used. The plastic cover incorporated a fitting for the suction pump lead, and two terminals for the electrical leads. Hanging straight down from one terminal was a pointed brass strip to which was soldered the platinum wire. Hanging vertically from the other terminal was a two inch piece of approximately 1/2 inch thick solid brass. Running through the lower end of this brass, and perpendicular to it in the direction of the other terminal was a steel machine screw, through the end of which, in a vertical direction, was secured a one inch piece of 1/16" brass tubing. Thus the electrodes were similar to those used in the wind tunnel and the spacing was obtained by adjusting the screw holding the brass tubing. The manometer was attached to the suction pump lead to measure the suction in inches of mercury and again to insure insulation, Acryloid was used heavily. In order to avoid any possible ionization of the air in the jar, the air was changed after each set of measurements at a particular pressure.

TESTING AND TEST DATA

The test data as recorded in Fig. 8 to Fig. 24, were obtained by sliding the probes, keeping the tip of the platinum wire just opposed the static orifice, into the tunnel to the desired location and securing the support to the steel track by means of the 1/4 inch bolts. Unfortunately due to vibration troubles the length of the cantilevered probes had to be shortened until the static orifice and wire could just be located in the throat. This unpredicted difficulty eliminated any testing upstream of the throat and all data had to be secured either in the throat or, as much as possible, downstream of the throat. The latter was of course limited. The flow in the throat could just be allowed to reach sonic velocity and then diffuse again subsonically aft of the throat. This is sometimes known as the first critical pressure ratio. If the flow reached supersonic proportions at any time, the static pressure readings aft of the throat were erroneous for subsonic speeds. (The only exception to this may be at the first critical pressure ratio when with certain type throats a small supersonic region may appear near the walls in the throat. Ref. No. 5). Somewhere between the static probe and the throat the supersonic flow would have to have broken down through a shock wave, with a corresponding entropy loss. These losses would have to have been computed and the static pressure reading

related to a new stagnation pressure (P_c'). Any downstream testing was then limited to the first critical pressure ratio and subsonic diffusion as dictated by effective area ratio. As a result, all testing was made in the vicinity of the throat to a point 1 1/2 inches downstream. This also greatly handicapped the obtaining of data, showing the effect of Mach number at constant pressure. As a result all data had to be referred to the characteristics curve for the particular static pressure under no flow conditions, and the effect due to Mach number noted. Only at a few isolated spots was it possible to observe the Mach number effect at constant pressure and this almost exclusively in the low speed range. Supersonically, of course, this problem was eliminated. Furthermore as expected since the platinum wire was directly opposed the static orifice, no effect on the pressure readings was had on the air flow measurements. With or without the wire probe in place, the static readings obtained were the same.

The spacing of the electrodes, which proved to be very important also left something to be desired. Although the spacing was measured prior to each run and checked after the run, there was believed to be some play in the arrangement of approximately 1/64 inch. This could alter the results significantly. Then too, since the platinum wire is small (.003 in. diameter), it too may have been attracted electrically towards the plate or even bent slightly due to the air velocity. This electric-

attraction was noticed once during static pressure tests in the jar. Visually this did not appear to happen in the tunnel but the human eye is a poor evaluator of very small distances. Magnifying glasses were available but due to an error in constructing the nozzle (solvent was allowed to pour down the walls) the original planned excellent optical properties were destroyed. Time was insufficient to have another nozzle constructed.

Before taking data, it became evident that the wire had to be "burned in", i.e. it had to be burned with a high glow for several minutes. This in effect, as observed under the microscope, had the result of slightly rounding the blunt edge of the cut wire. The characteristics changed during this burning in with the current decreasing and it was only when the edges were rounded and character-istics became steady and reliable that testing could be accomplished. This verifys some of Fucks' work as the ion velocity is changed by the point size and sharpness. Burning in at 200 microamperes for two to three minutes proved to be satisfactory.

The data was obtained then simply by securing the probes in place, as near the throat, and establishing an air flow. The stagnation pressure and static pressures were recorded from the manometer and the characteristics obtained by increasing the voltage and noting the current. This was generally continued until the wire flashed as evidenced by a sharp drop in current, sound and the

observer's eye. The glow was clearly visible in subdued light at near atmospheric pressure and very noticeable in daylight at reduced pressures.

Testing with another size platinum wire (.001 in.) was also attempted and with opposed polarity. The latter was accomplished merely by changing the leads to the probes and using the other circuit. The pressure measurements in the jar were conducted, after securing any leakage, by setting a desired pressure by the use of a suction pump as read from the manometer and reading the glow characteristics. After each pressure, the air was allowed to return to atmospheric conditions to dispel any possible ionization of the gas. This last procedure was not necessary during tests in the wind tunnel, since according to Kuchter, an electrical field about a body has a strong influence on the air stream only if a high intensity field is set up, (100,000 to 200,000 volts) and then only up to velocities in the order of 65 ft./sec. (M = .06).

RESULTS AND DISCUSSION

The data as obtained appears in Fig. 3 to Fig. 24. In order to obtain a zero Mach number curve at any pressure, the data as given in Fig. 8 was cross plotted at constant amperage in Fig. 9. These curves at the desired pressures, were then compared to the data taken at the same pressure but with impressed flow. As the air was at all times extremely dry, no correction need be made for humidity and, according to the work of Werner, the glow is insensitive to temperature. For a particular arrangement of electrode material, size and spacing, the only variables expected to be encountered were pressure and velocity. It may be that this assumption was in error. The platinum wire used was always approximately 1/32" long and for a seemingly good reason. On several occasions wires 1/16" long were used and the characteristics were noted to be slightly different. With zero velocity, the amperage with the longer wire appeared one to two micro-amperes higher. Thus it may be in the arrangement used that the current is related not only to the size wire, the point size and the spacing between the electrodes but also to the length of the wire. This is understandable as now more area is subjected to ion bombardment and a greater avalanche could take place, yielding more current. To avoid this possibility, the wires were cut to approximately 1/32 inch length for all tests. With impressed velocity, an effect of this length could also be

expected as a longer region of ion flow and a greater number of charge carriers may be subjected to being blown away. A wire too long and slender would, of course, not be feasible as it would be subject to bending and vibration when in a flow stream. This possibility should be investigated further.

Immediately evident from Fig. 8 and 9 is that the glow discharge is very sensitive to pressure changes with the intensity increasing as the pressure is reduced due to the reduced density, larger mean free path of the molecules and diffusion of the electrons. This is as expected and thus it lends itself to the possibility of measuring pressures in wind tunnels. The pressure could be tapped into a tightly sealed container to eliminate the effect of Mach number and characteristic readings taken, giving the pressure and the corresponding Mach number. Although a pressure survey at high pressures was not included, it is expected that such glow discharge characteristics can be obtained and thus extending the glow's use to reading stagnation and total head pressures. A survey should be made of the characteristics at high pressures and it is expected that voltage in the order of 20,000 to 30,000 volts shall be required. The original survey was conducted with a smaller wire, namely, .001 inches in diameter in an endeavor to correlate previous work. Several tests were made at Mach numbers below 0.3

with very erratic results and no reproducibility of results. At tests above this Mach number, no current could be obtained and investigation showed that the wire had bent itself back around the insulation material of the probe. At supersonic speeds, the needle was blown away on four successive attempts and it was concluded that the wire was too small and flexible for velocity measurements. All tests were then conducted with .003 inch wire which proved to be satisfactory.

Similarly the first tests were to be made with the platinum wire as the positive electrode and it was expected that the current would be very small. In every attempt, arcing was experienced before any amperage readings could be made. The microammeter needle was observed to make several small unsteady movements just prior to the arcing but proved insensitive to any current that may have been flowing. It was immediately apparent that a negative wire was more sensitive and useful and no further tests were made with a positive wire.

In previous work with direct current glow discharge anemometers, the greatest disadvantage had been the burning away of the electrodes. However, in all these experiments it was noted that similar materials were used for anode and cathode and the arrangement of electrodes was very symmetrical. This burning away is believed due to the high temperature due to burning, oxidation in active

oxygen of discharge O_2 at lower temperature and cathode sputtering. This burning away was satisfactorily avoided by using an asymmetrical arrangement of electrodes as suggested by Fuchs, using a noble metal, platinum, with its high resistance to oxidation and generally restricting the amperage to a hundred microamperes or reducing the voltage immediately upon any evidence of sputtering or sparking. It is to be noted that transition to sparking was very sharp and care had to be taken to reduce the voltage quickly, less possible damage to the installation result.

The data obtained was recorded as a function of Mach number as a parameter since the work was carried out in a wind tunnel. However, as the local velocity of sound decreases less than 100 ft./sec. over the range of Mach numbers due to the temperature drop, it is to be understood that the velocity change is almost linear, varying from [illegible] ft./sec. at a Mach number of [illegible] to [illegible] ft./sec. at M = [illegible]. Thus for each one-tenth change in Mach number, a corresponding change of [illegible] ft./sec. may be assumed as approximately correct, the error not exceeding 7 ft./sec. The stagnation chamber temperature was assumed constant for all runs.

In Figs. [illegible] to 10 are plotted the results of using the electrodes [illegible] inches apart. Immediately it is obvious that the glow is sensitive to Mach number but not

until a Mach number of about 0.30 is reached (331 ft./sec.). Many tests were conducted at lower Mach numbers, and on occasion slight sensitivity noticed especially at low amperage. However, the majority of results showed no displacement of the curve and as the curves turned toward a vertical tangent, results were erratic. They may have been due to slight fluctuations in the voltage at these critical points or possible sputtering. This lack of response is understandable as the ion velocity is very high compared to the velocity of flow of the air molecules. As the air flow is increased response could be expected and as indicated, this was true at all Mach numbers above 0.303. Fig. 11 shows results at the same pressure for different velocities indicating a marked displacement of the curve for the increased velocity. The reversal of the curve at the lower current is expected to be in error as in most tests, the lower limits were not well defined. It is also well to note that the point of ignition appeared to increase in current as the velocity increased.

Fig. 12 gives a good comparison of the same Mach number at two different pressures and while it indicates a very similar effect in the low amperage range, the higher pressure appears more sensitive as the current is increased. A device should be constructed that would allow the testing of the same velocity up to the speed of sound and slightly above, at the same pressure. Such a device could be a wind tunnel with the throat downstream

of the probes and a very small angle convergence to the throat. This small angle convergence would be necessary since the area ratio controlling the Mach number from 0.40 to unity only changes from 1.59 to 1.00. There also should be a means of changing the stagnation temperature, thus changing the velocity at a constant Mach number. The tunnel used could not be so designed since, as it was to be used supersonically and had a small throat, the boundary layer could not be allowed to build up excessively.

Reproducibility of results at this 1/8 inch spacing was fair with very similar curves resulting, many being displaced slightly, and this generally towards higher amperage for the same voltage. These fluctuations it is feared may have been due to slight bending of the wire or vibrations due to the force of the flow. The wire probe was always at an angle to the flow, due to the thickness of the probes and to insure good insulation, and any bending would have been towards a closer spacing and a correspondingly higher current.

The variation in voltage at constant current appears in Fig. 15. There is good sensitivity up to $M = .75$ for amperage below 12 microamps and up to $M = .75$ for higher amperage but above these limits the curves are mixed and show a drop in sensitivity. There is no apparent theoretical reason for this drop in the vicinity of $M = 1.0$ and it may be due to either poor experimental results, a bending wire, or a decrease in sensitivity of

lower pressures as all tests in this regime were conducted necessarily at reduced pressure. The scatter of points is also believed due to the fact that the Mach numbers were obtained at various static pressures with the assumption that the response was similar at all pressures. This assumption should be closely investigated. These curves also indicate that sensitivity to velocity can be had at lower Mach numbers in the order of 0.20 instead of as evidenced at 0.31.

At constant voltage the sensitivity to amperage drop as velocity is increased is good but the range is definitely limited at each voltage. Sensitivity is good at a particular voltage until a near vertical tangent is experienced with respect to current. The pressure is a very important factor here with a higher voltage required for a higher pressure. Thus the curves shown are merely representative of what occurs since each is plotted over a range of pressures (hence the scatter of points) with those of lower voltage being taken over a reduced pressure range. Nevertheless, good sensitivity can be expected and again constant pressure lines of constant voltage must be obtained.

In Fig. 17 to 24 the data obtained for a 1/4 inch electrode spacing is plotted and as is expected, higher voltages are required for the larger spacing. This larger spacing, however, means that the anode to cathode travel is greater and the ions are subjected to

the flow for a longer time. Thus the sensitivity, especially at lower velocities, should be increased. Such is the case experienced (Fig. 19) with results obtained at M = 0.18 (205 ft./sec.) and from the plots of constant current and constant voltage, results may be obtainable with finer equipment down to M = 0.13 (145 ft./sec.). Should a probe be desired for very slow flow, it is anticipated that .001 inch wire with a large enough spacing would be more sensitive. However, since flow of such small magnitude is generally of little interest in aerodynamics, the possibility was not investigated.

Test at slightly different pressures (not exceeding 2" Hg. differential) up to a Mach number of 0.3, showed excellent correlation of data with the Mach number effect being very close to constant and the reproducibility excellent. Above this velocity tests could only be conducted at one pressure for each Mach number but the reproducibility remained good. The wire probe was not as inclined to the flow as with the smaller spacing and the vibrations apparently were reduced.

The variation in voltage at constant amperage was similar to that at the eight inch spacing but was a little more sensitive and restricted to a Mach number of 0.55. The curves of constant voltage were also similar but displayed a greater sensitivity. Again constant pressure curves are essential.

Thus it can be seen that spacing has a profound

effect both as to the voltage required, the range of the velocities (a larger space is sensitive to lower velocity), and the sensitivity to velocity change.

Consequently the glow discharge lends itself to use as a pressure probe, which has many uses such as in wind tunnels and pressure surveys in power plants or over surfaces. It also can be used as a velocity meter either in a wind tunnel or as an aircraft air speed indicator. Since it is insensitive to temperature, it cannot be used as a machmeter for, as in an aircraft, one may be travelling at 600 kts. true air speed which at sea level would be a Mach number of approximately 0.91 but at 35,000 feet it would be in the order of M = 1.05, all due to the change in temperature. Above this altitude to about 100,000 feet, the Mach number would be constant due to a constant temperature but the pressure would continue to drop. If the velocity response of the glow discharge is irrespective of pressure the indications would be the same at all altitudes which would give an incorrect Mach number. If it is responsive according to pressure, above 35,000 ft. it would show a changing response but the Mach number would not have changed.

When observed in the wind tunnel, the glow at first appeared to dim as the velocity was increased but as the velocity increased further the glow increased in intensity. This latter increase was undoubtedly due to the reduction in pressure. The location of the glow did not

appear to change at any time.

CONCLUSIONS

From the foregoing study the following conclusions may be made:

1. The glow discharge characteristics at a wire point are a function of the materials, size, spacing and polarity of the electrodes. They may also be a function of the length of the wire electrode.

2. The glow discharge is pressure sensitive and as such lends itself to use as a possible pressure probe in a wind tunnel to measure such items as static pressure and quite possible, high stagnation and total head pressures. Less voltage is required to maintain a constant current as the pressure decreases.

3. The glow discharge is also velocity sensitive, the sensitivity and range being a function of the electrode spacing, and wire size. Higher voltage is required to maintain a constant current as the velocity increases.

4. A platinum wire, .001 inches in diameter proved to be too small and flexible for velocity measurements. A wire .002 inches in diameter was used for all tests.

5. It is necessary that the wire electrode be made the negative electrode as no results could be obtained when using positive polarity.

6. The burning away of the electrodes previously experienced, can be avoided by using different size electrodes of different materials with the wire electrode being made of platinum, a material highly resistant to

oxidation.

7. The glow discharge, while velocity and pressure responsive, cannot be used as a Machmeter due to its insensitivity to temperature.

8. The glow discharge, when subjected to air flow, is more sensitive to voltage changes at constant current than to current changes at constant voltage and this sensitivity increased with increasing electrode spacing.

It is recommended that further studies be carried out to determine the following:

1. The effect of wire size and length on the characteristics and velocity sensitivity. Wires up to 0.01 inches in diameter should be tested in lengths varying from 1/8 to 1/4 inch.

2. The velocity effect at constant pressure over a wide range of pressures.

3. The pressure sensitivity of the glow at pressures up to 250 psia.

4. The effect of electrode spacing to velocity sensitivity over a wider range, preferably from 1/16 to 1 inch.

5. Subsonic and supersonic studies be carried on jointly to afford a wide range of application.

BIBLIOGRAPHY

1. "The Stability of a Dark Current Discharge for the Measurement of Flow Velocities of Gases", Wilhelm Fucks, German Aeronautical Research Institute, Berlin, 1942.

2. "Investigation of the Possible Utilization of an Electrical Glow Discharge as a Means for Measuring Air Flow Characteristics", Frank D. Werner, Thesis for the Degree of Master of Science, University of Minnesota, November, 1948.

3. "Fundamental Processes of Electrical Discharge in Gases", L. B. Loeb, John Wiley and Sons, Inc., New York, 1939.

4. "Kinetic Theory of Gases", E. H. Kennard, McGraw-Hill Book Co., New York, 1938.

5. "Tests with an Alternating Current Glow Anemometer under Steady Conditions", Wilhelm Fucks and Gerd Schumacher, German Aeronautical Research Institute, Berlin, 1944.

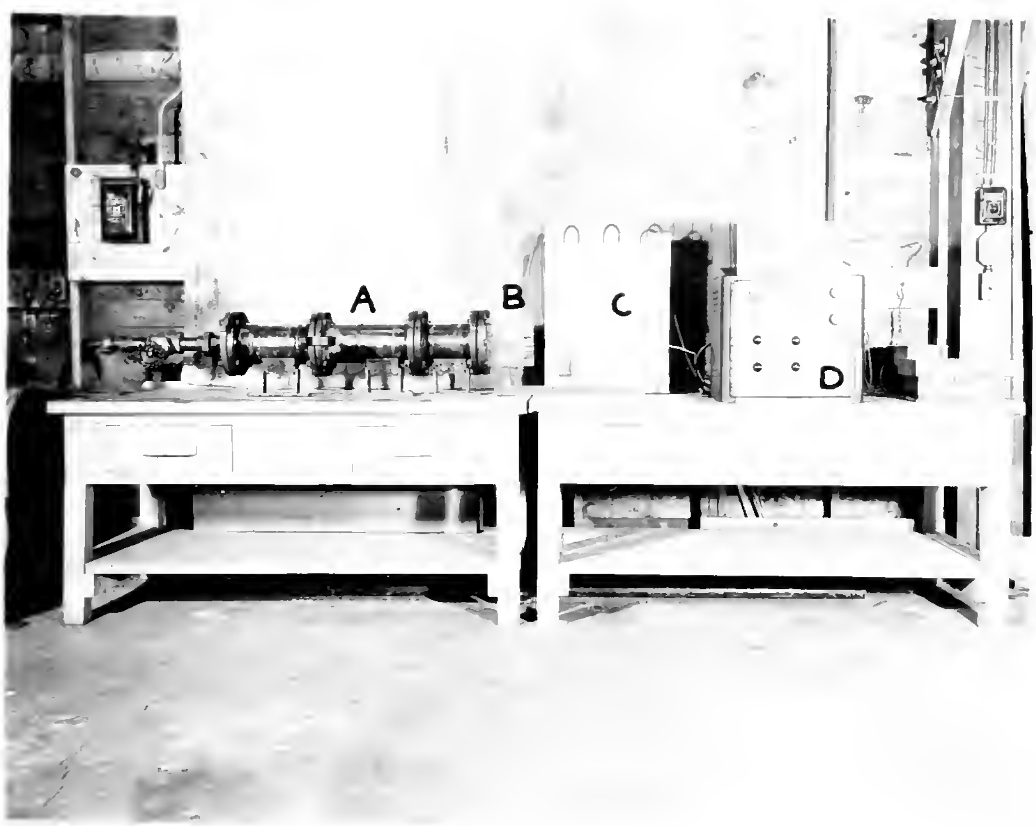
6. "Aerodynamics of a Compressible Fluid", H. W. Liepmann and A. E. Puckett, John Wiley and Sons, Inc., New York, 1947.

7. "Gas Tables", J. H. Keenan and J. Kaye, John Wiley and Sons, Inc., New York, 1948.

8. "Flow Pattern in a Converging Diverging Nozzle", K. Oswatitsch and W. Rothstein, NACA TM. No. 1215, March, 1949.

9. "Influence of an Electric Field on the Air Flow Around a Body", G. Richter, Translation from German wartime reports.

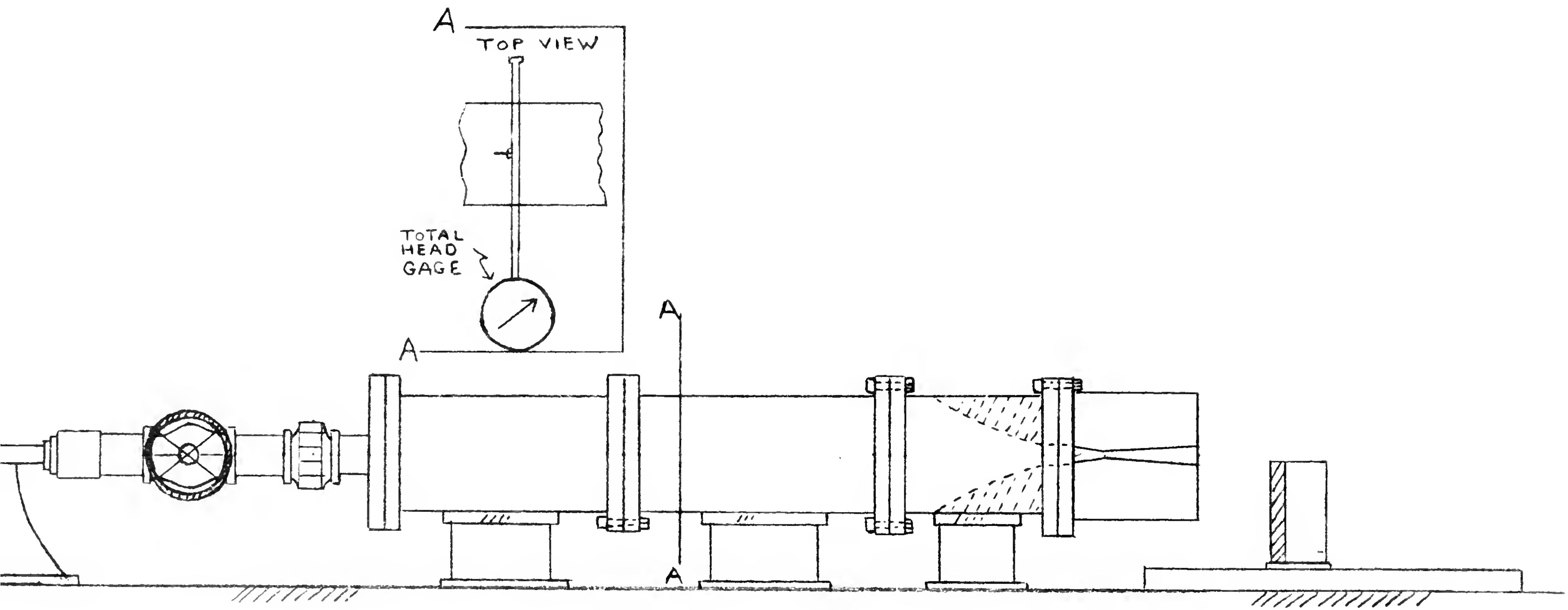
10. "Investigation of the Possibility of Utilizing an Electrical Glow Discharge as a Velocity Meter at Supersonic Speeds", R. [illegible] Bollenberger, Thesis for the Degree of Master of Science, University of Minnesota, July, 1949.



LABORATORY EQUIPMENT

A - STAGNATION CHAMBER
B - NOZZLE
C - MANOMETER BOARD
D - ELECTRICAL PANEL

FIG 1

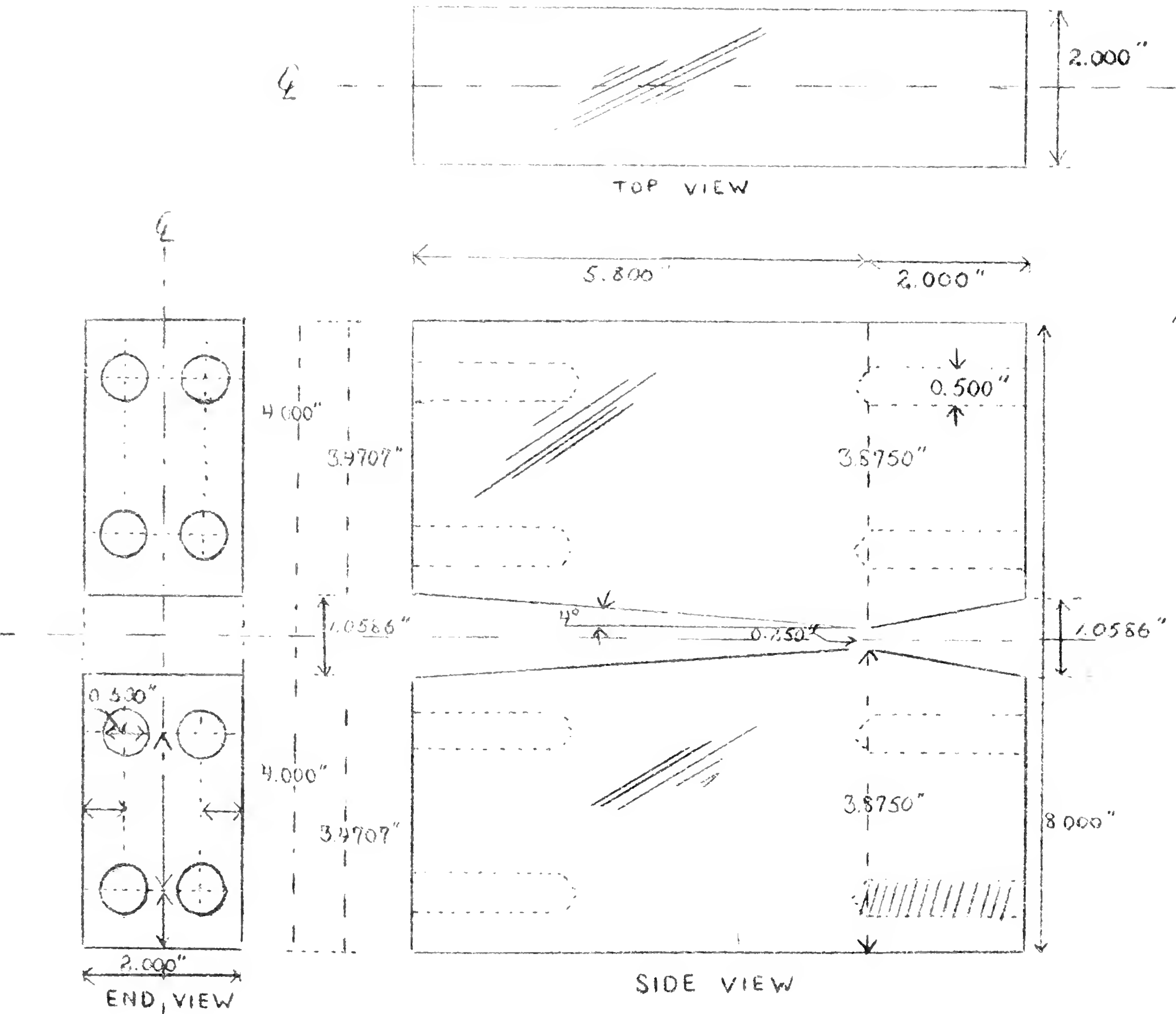


SIDE VIEW

WIND TUNNEL

FIG 2

SCALE $1/10'' = 1''$



NOZZLE BLOCK DESIGN

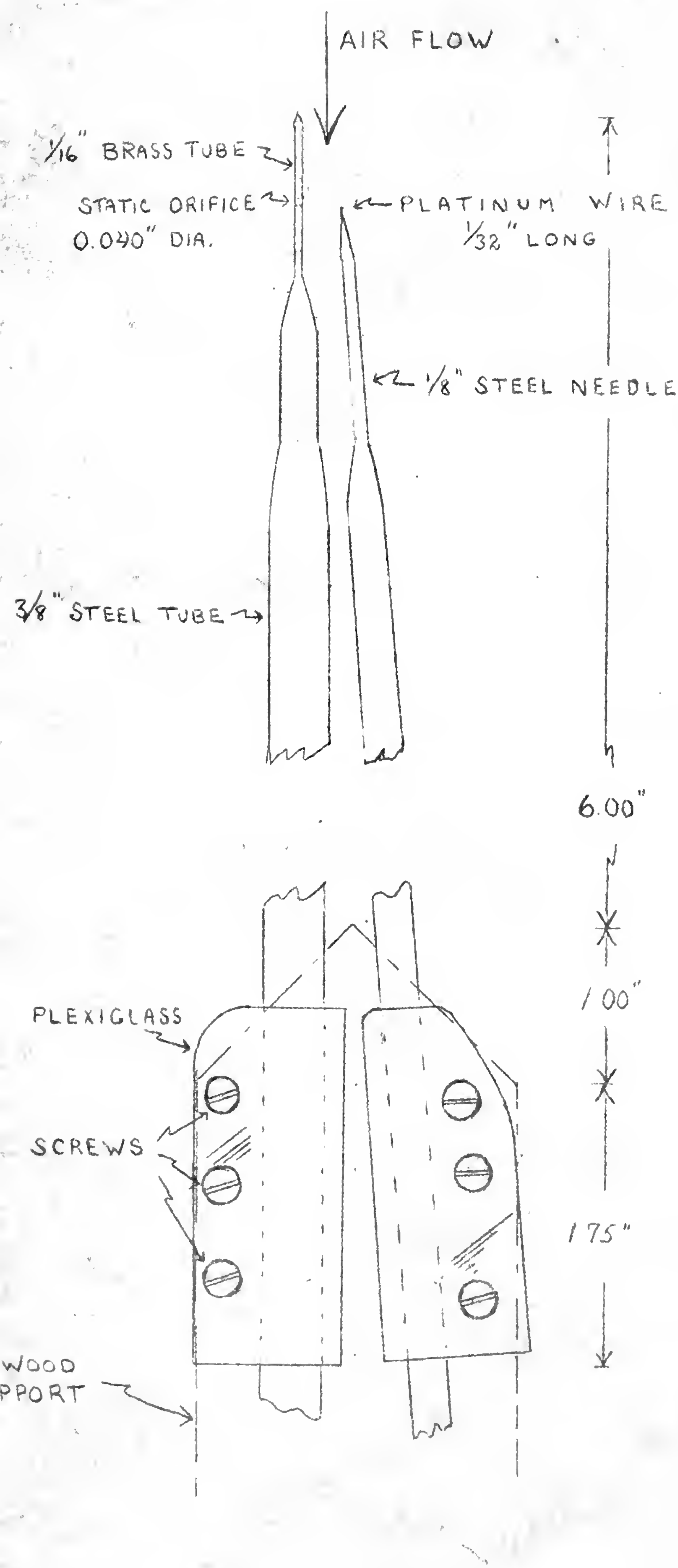
FIG 3

PRESSURE SURVEY JAR, NOZZLE AND PROBES

FIG 4

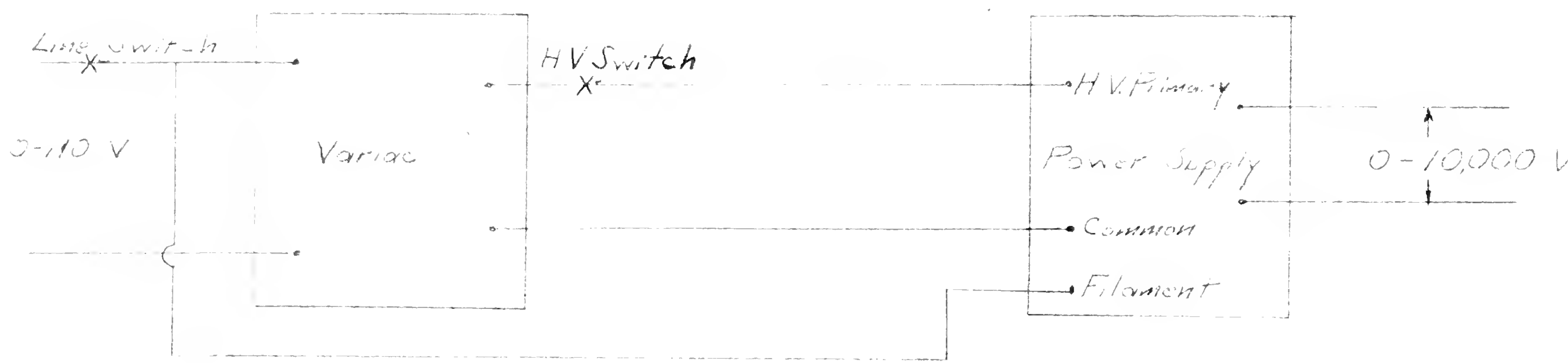
SHADOWGRAPH of the PROBES

FIG 4A



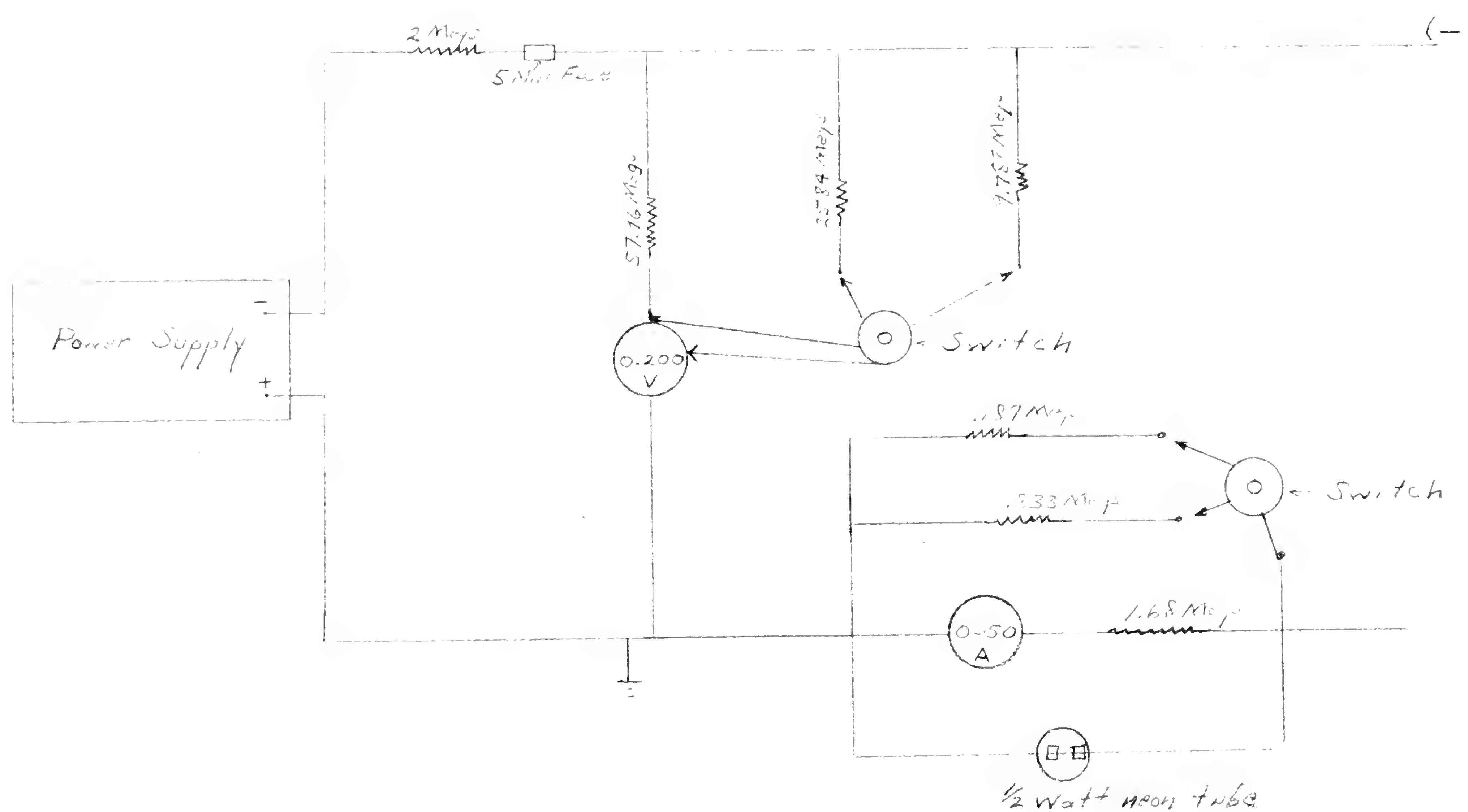
ARRANGEMENT of the PROBES

FIG 4B



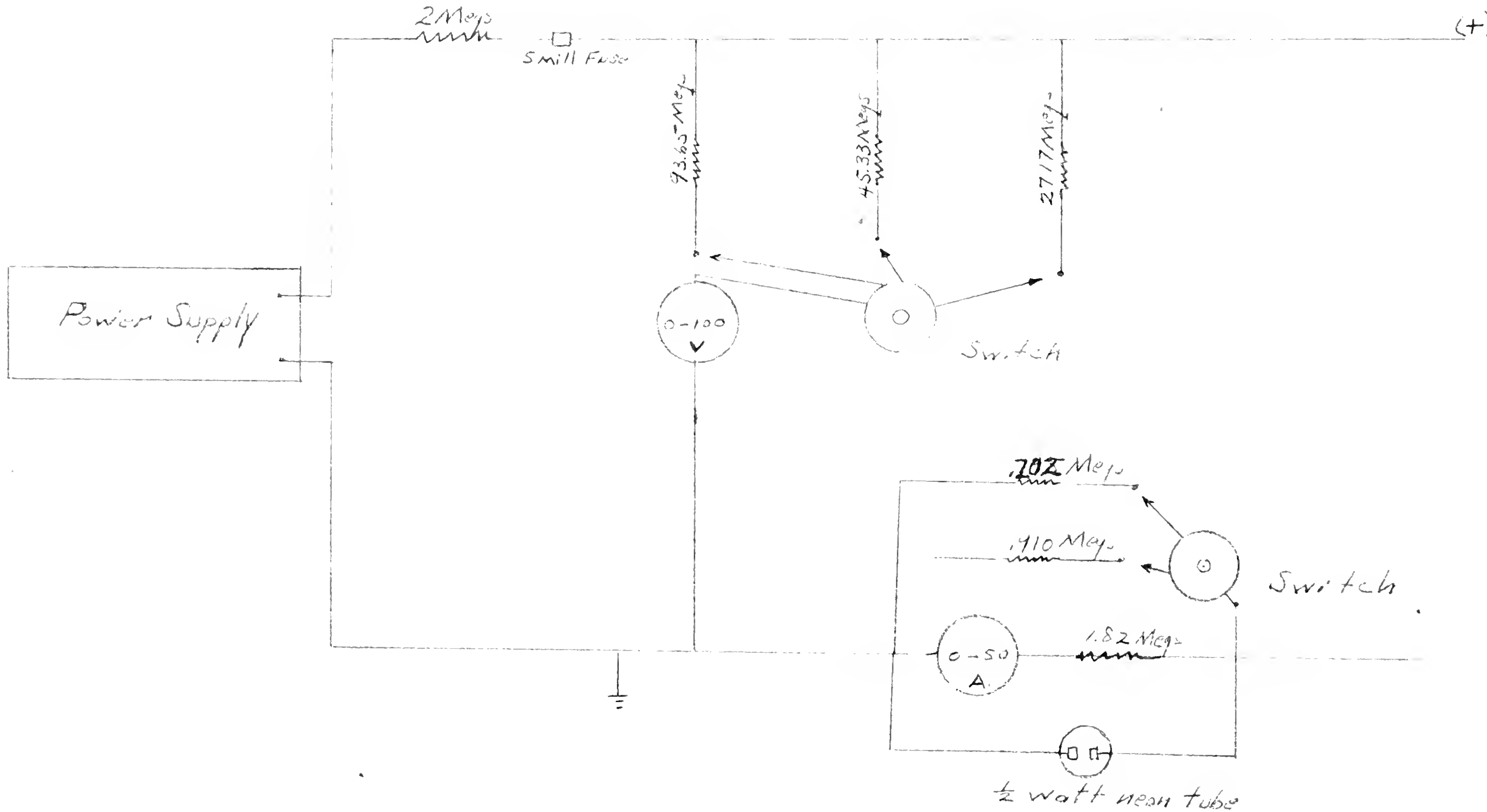
Power Supply

FIG 5



Circuit # 1

FIG 6



Circuit #2

FIG 7

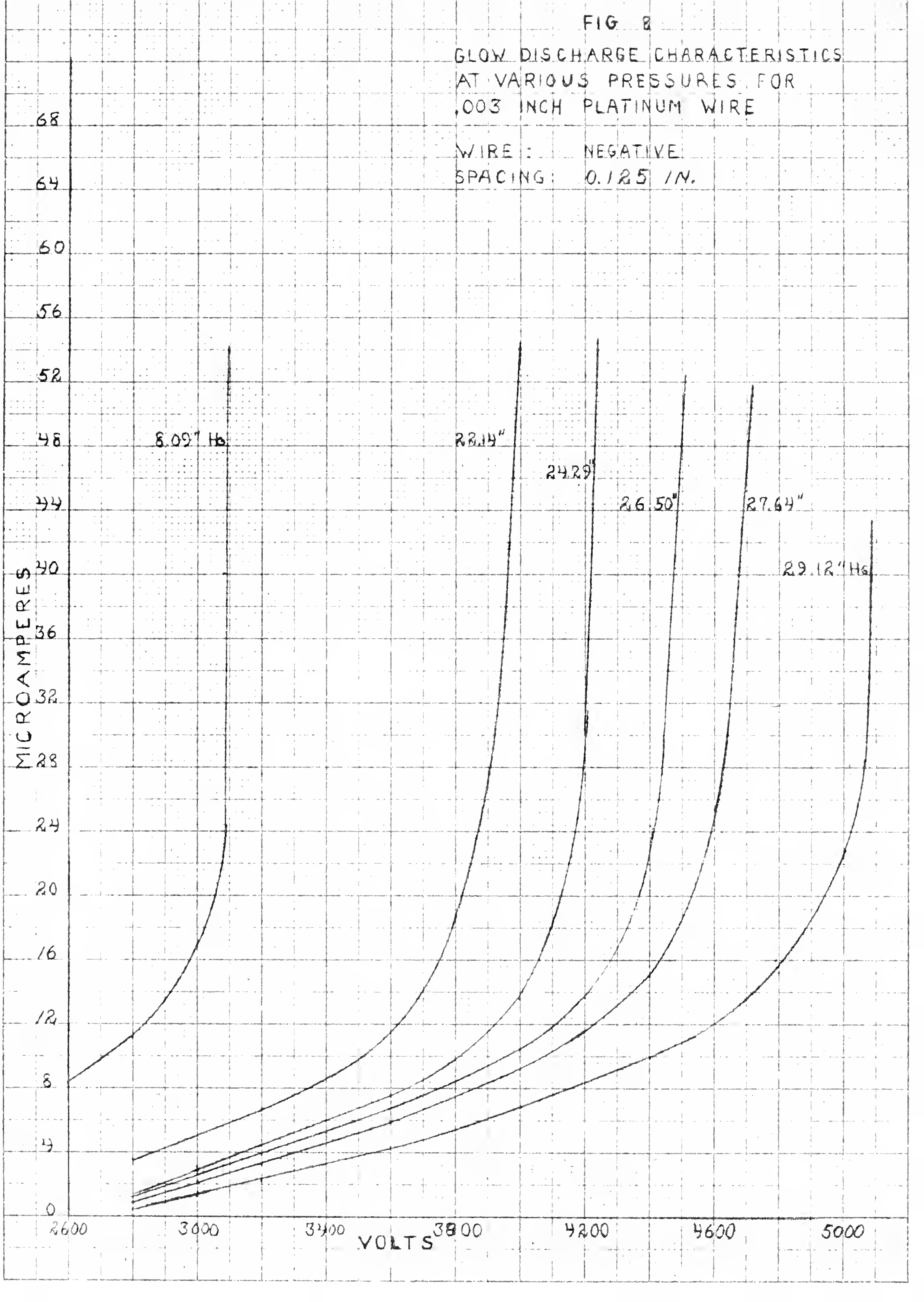


FIG 8
GLOW DISCHARGE CHARACTERISTICS AT VARIOUS PRESSURES FOR .003 INCH PLATINUM WIRE
WIRE : NEGATIVE
SPACING: 0.125 IN.
8.09" Hg
22.14"
24.29"
26.50"
27.64"
29.12" Hg
MICROAMPERES
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
VOLTS
2600
3000
3400
3800
4200
4600
5000

FIG 9

GLOW DISCHARGE CHARACTERISTICS - SHOWING CONSTANT MICROAMPERAGE LINES FOR .003 IN. PLATINUM WIRE

WIRE: NEGATIVE
SPACING: 0.125 IN.

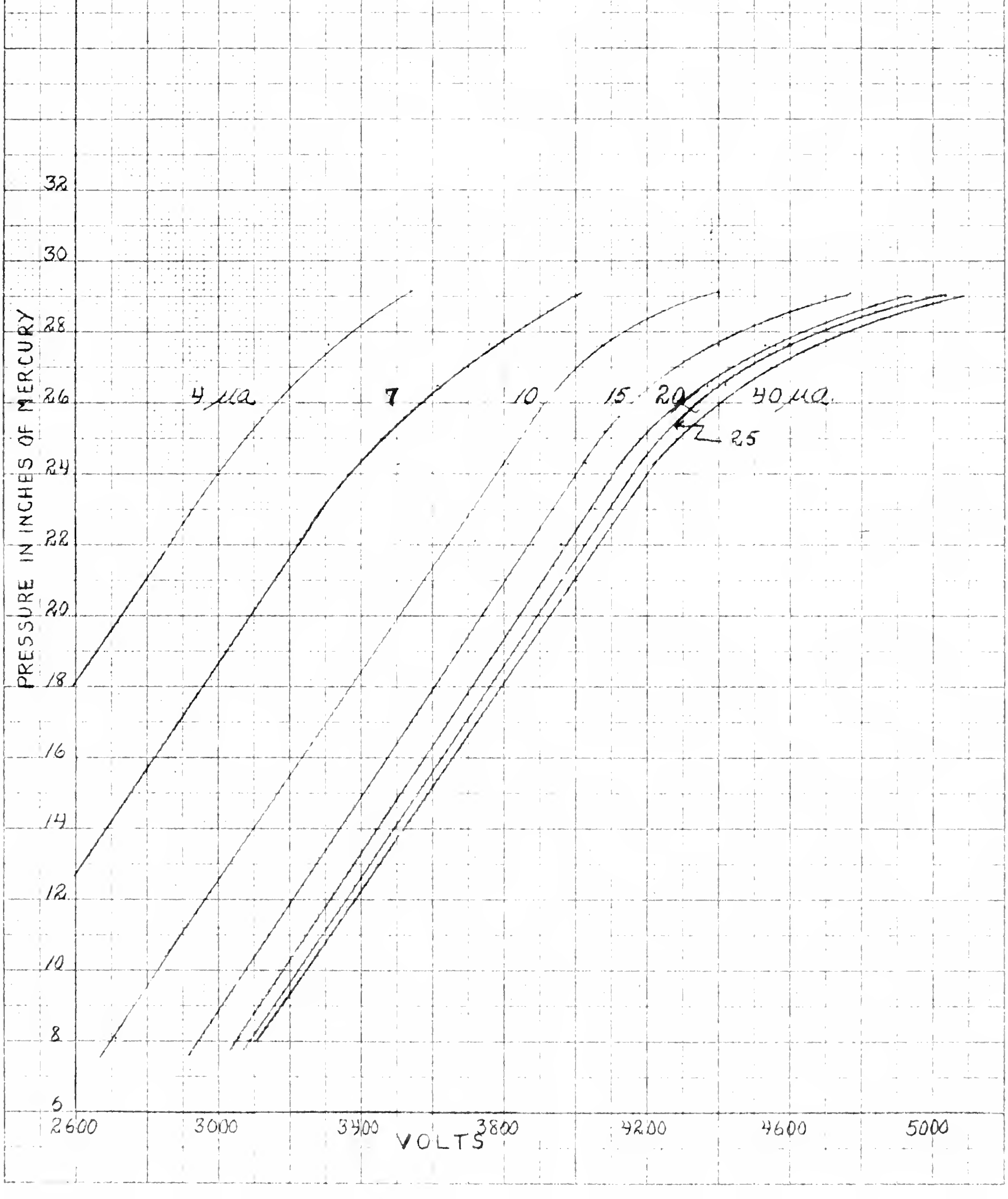
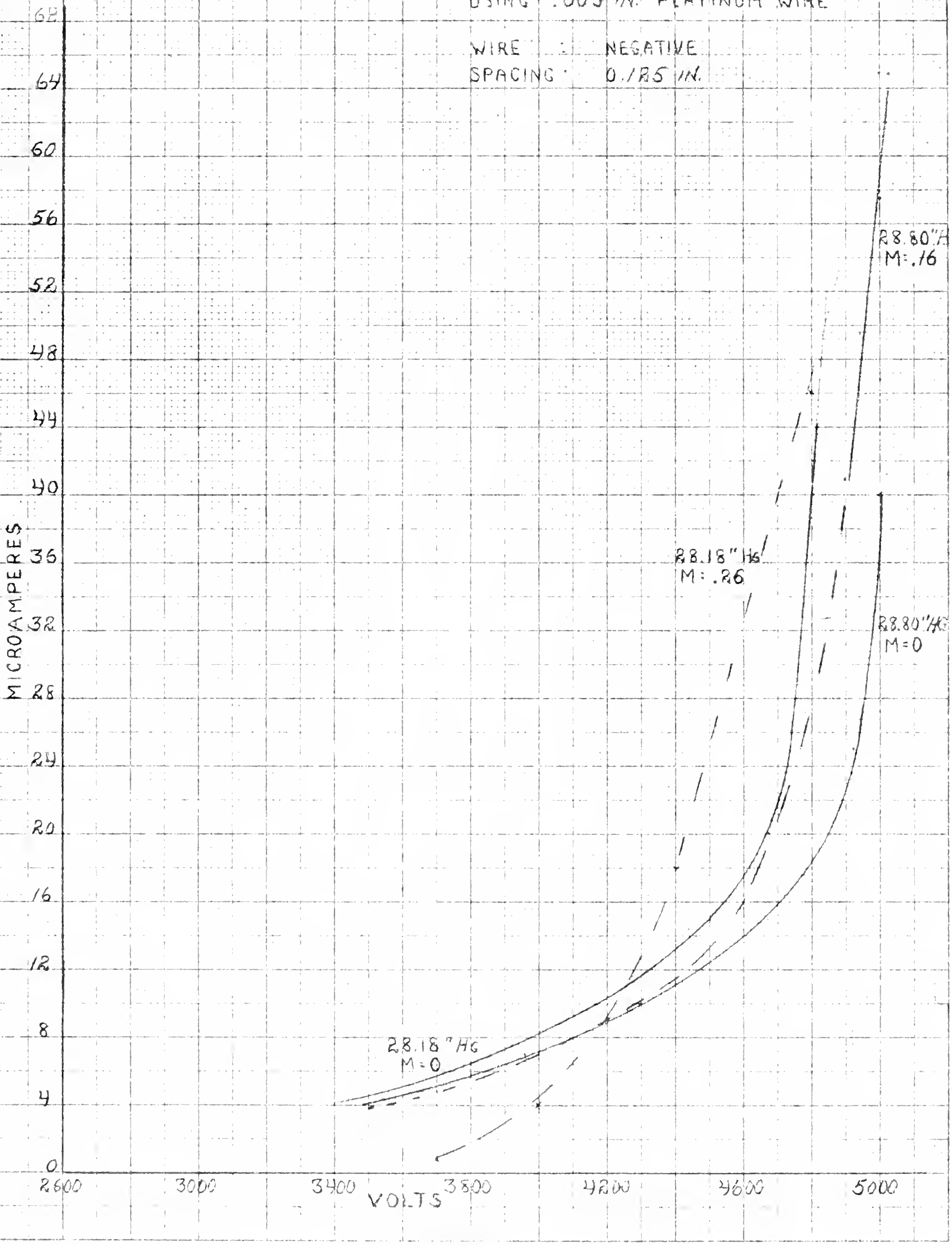


FIG 10

GLOW DISCHARGE CHARACTERISTICS
SHOWING MACH NUMBER EFFECT
USING .003 IN. PLATINUM WIRE



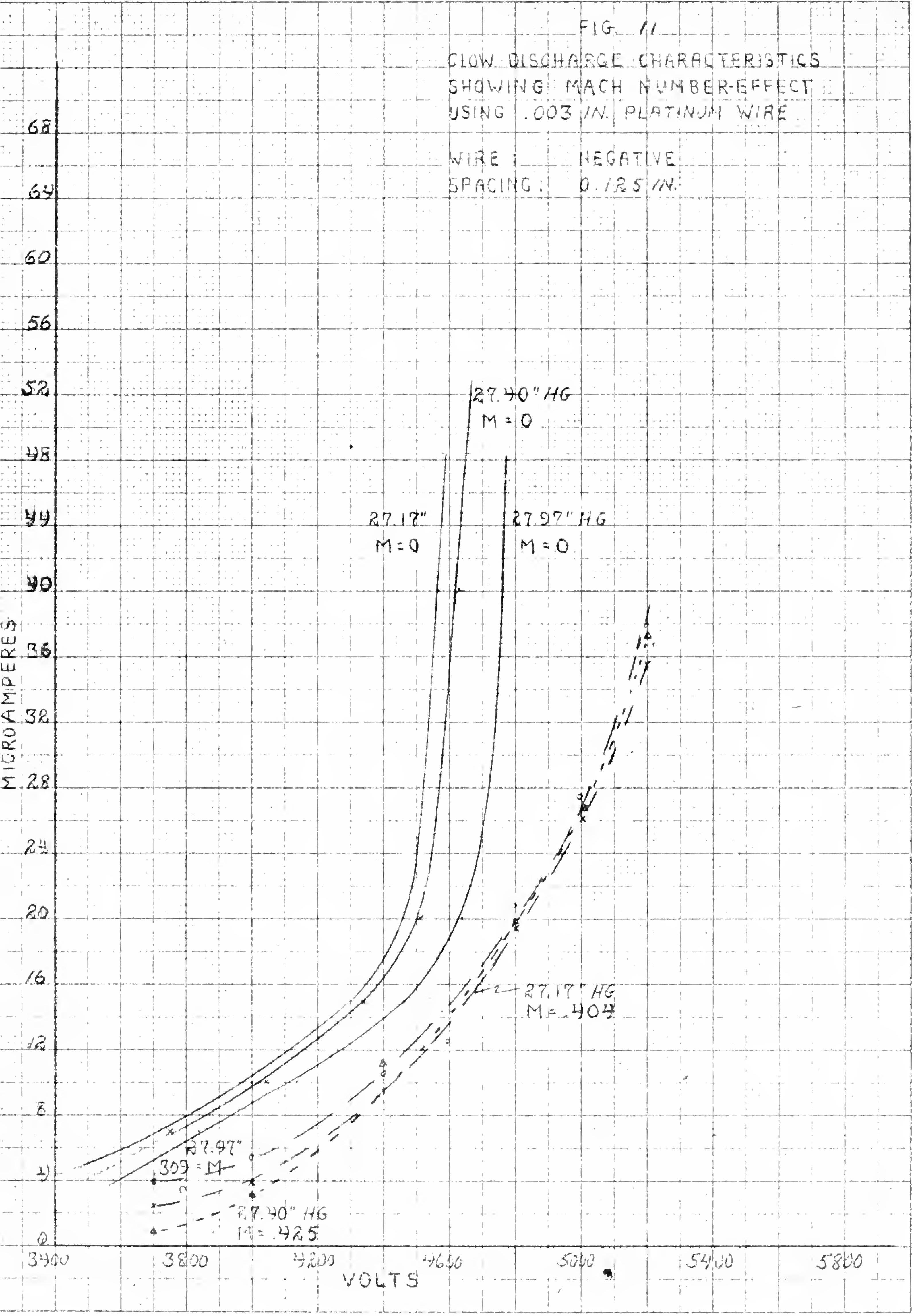


FIG. 11
GLOW DISCHARGE CHARACTERISTICS
SHOWING MACH NUMBER EFFECT
USING .003 IN. PLATINUM WIRE
WIRE : NEGATIVE
SPACING : 0.125 IN.
27.40" HG
M = 0
27.17"
M = 0
27.97" HG
M = 0
27.17" HG
M = .404
27.97"
.309 = M
27.40" HG
M = .425
MICROAMPERES
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
3400
3800
4200
4600
5000
5400
5800
VOLTS

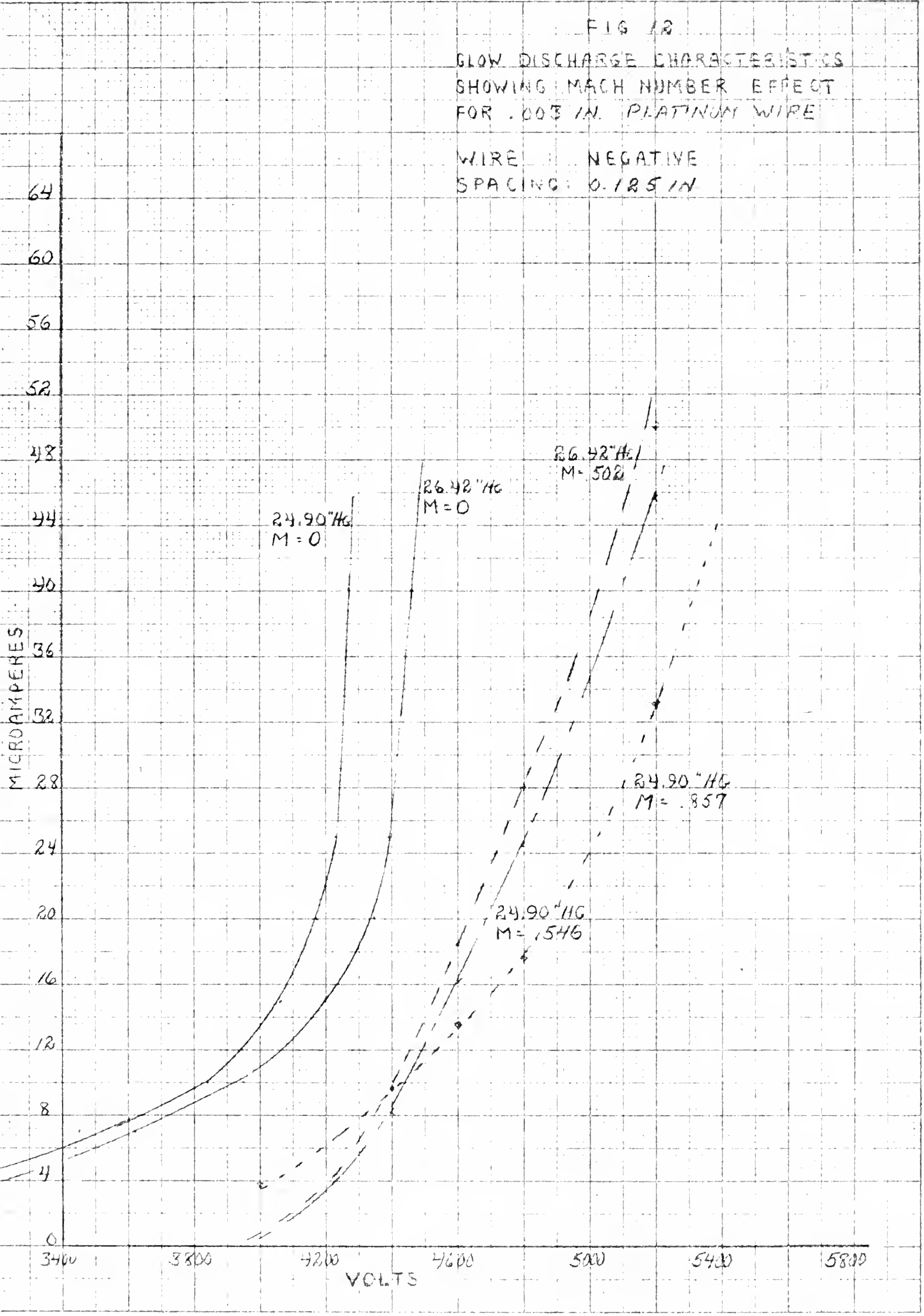


FIG 12
GLOW DISCHARGE CHARACTERISTICS
SHOWING MACH NUMBER EFFECT
FOR .003 IN. PLATINUM WIRE
WIRE : NEGATIVE
SPACING: 0.125 IN
MICROAMPERES
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
3400
3800
4200
4600
5000
5400
5800
VOLTS
24.90"HG
M = 0
26.42"HG
M = 0
26.42"HG
M = .502
24.90"HG
M = .857
24.90"HG
M = .546

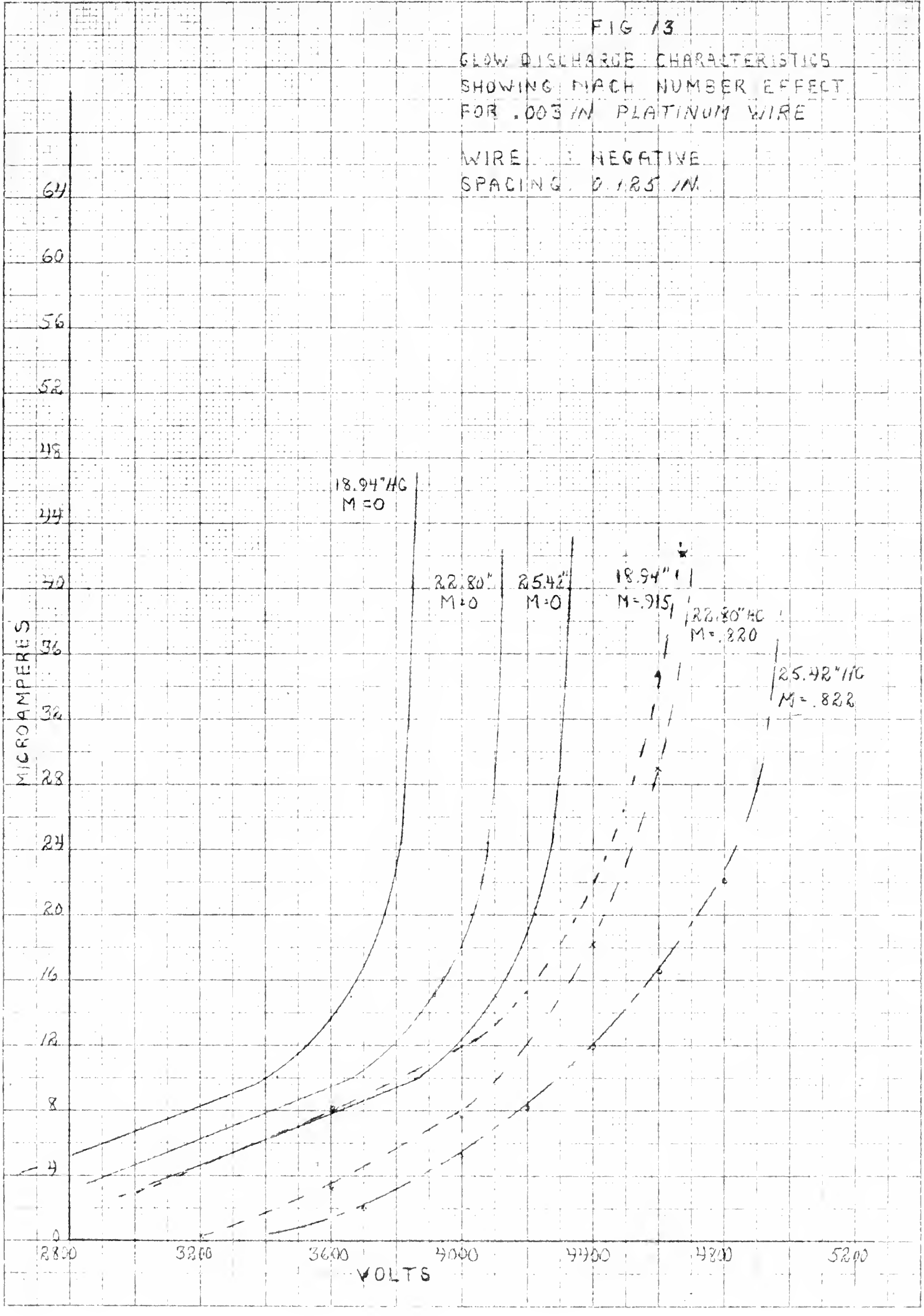


FIG 13
GLOW DISCHARGE CHARACTERISTICS
SHOWING MACH NUMBER EFFECT
FOR .003 IN PLATINUM WIRE
WIRE : NEGATIVE
SPACING 0.125 IN.
18.94"HG
M=0
22.80"
M=0
25.42"
M=0
18.94"
M=.915
22.80"HG
M=.820
25.42"HG
M=.822
MICROAMPERES
VOLTS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
2800
3200
3600
4000
4400
4800
5200

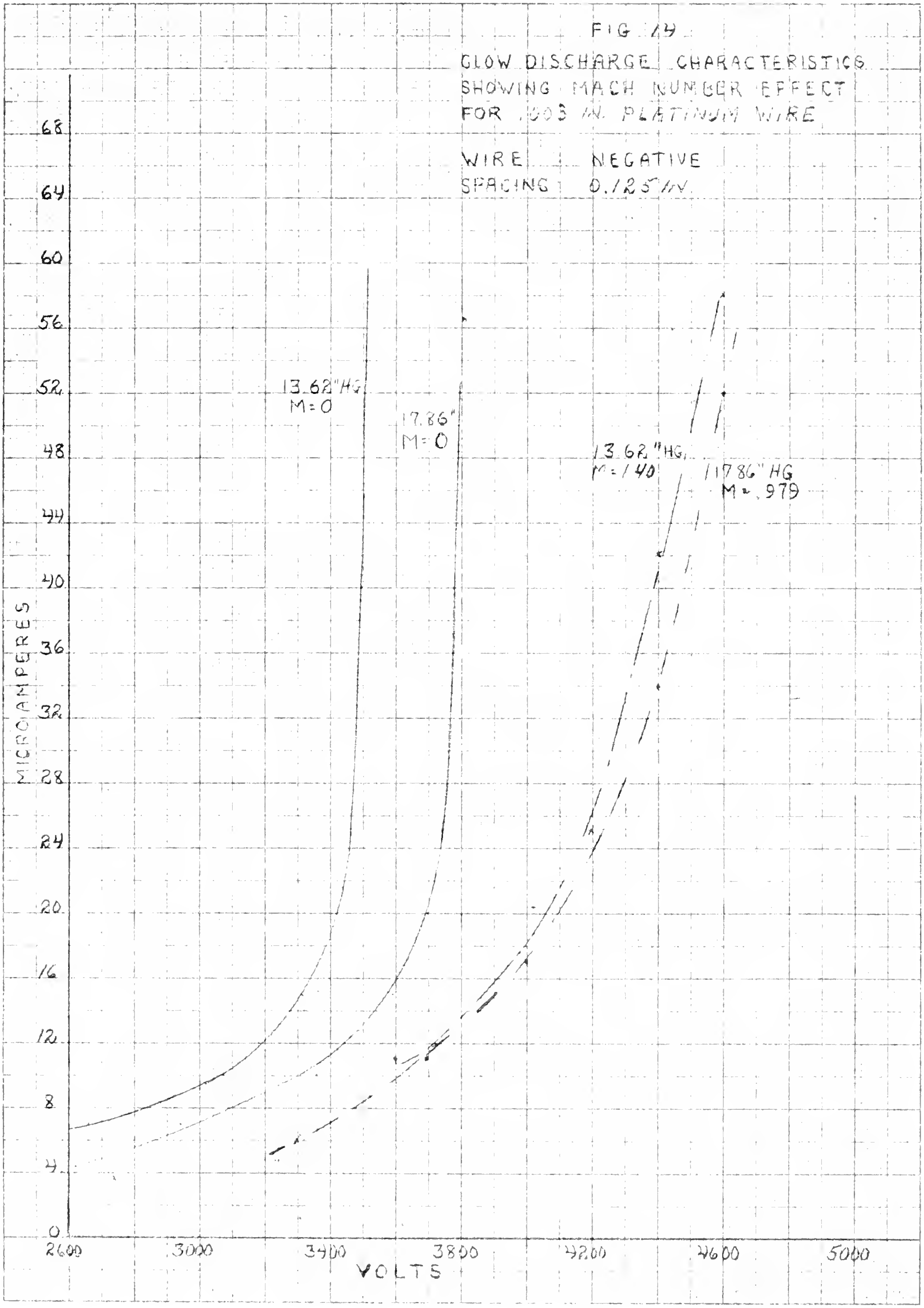
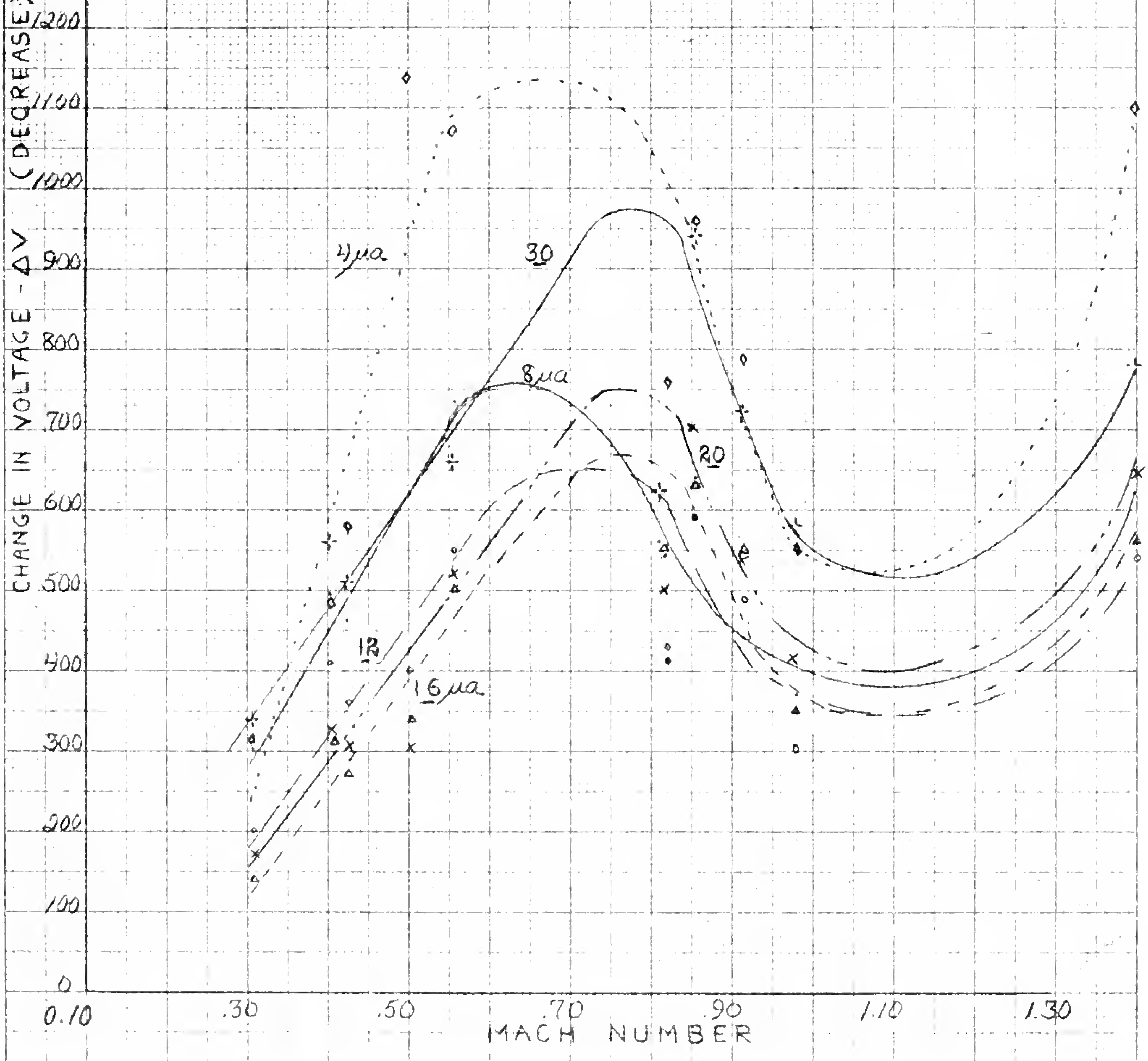


FIG 14
GLOW DISCHARGE CHARACTERISTICS
SHOWING MACH NUMBER EFFECT
FOR .003 IN. PLATINUM WIRE

FIG 15

GLOW DISCHARGE CHARACTERISTICS
SHOWING THE VARIATION IN VOLTAGE
AT CONSTANT AMPERAGE DUE
TO MACH NUMBER
FOR .003 IN. PLATINUM WIRE

WIRE NEGATIVE
SPACING: 0.125 IN.



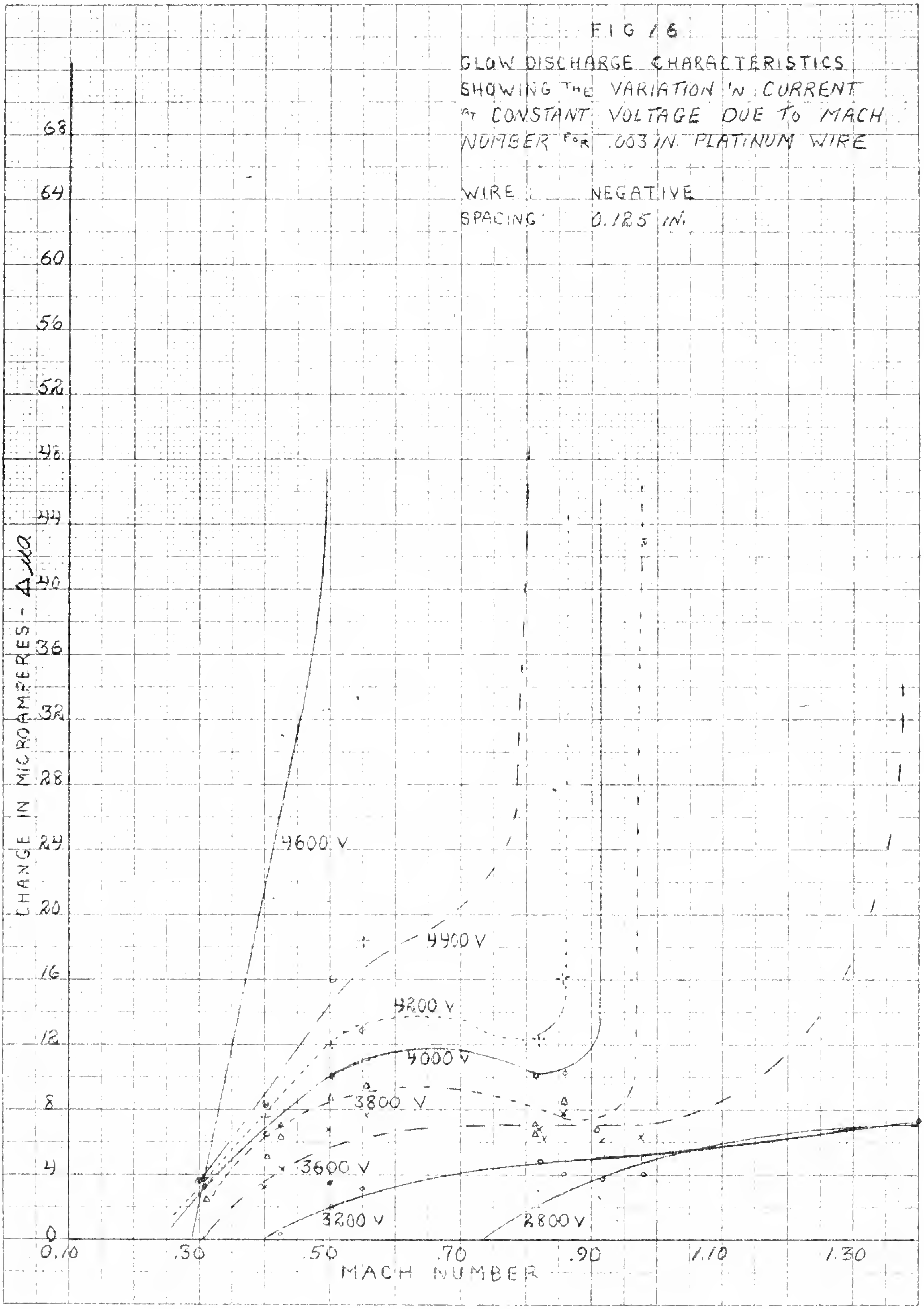


FIG 16
GLOW DISCHARGE CHARACTERISTICS SHOWING THE VARIATION IN CURRENT AT CONSTANT VOLTAGE DUE TO MACH NUMBER FOR .003 IN. PLATINUM WIRE
WIRE: NEGATIVE
SPACING: 0.125 IN.
CHANGE IN MICROAMPERES - Δ μa
MACH NUMBER
4600 V
4400 V
4200 V
4000 V
3800 V
3600 V
3200 V
2800 V
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
0.10
.30
.50
.70
.90
1.10
1.30

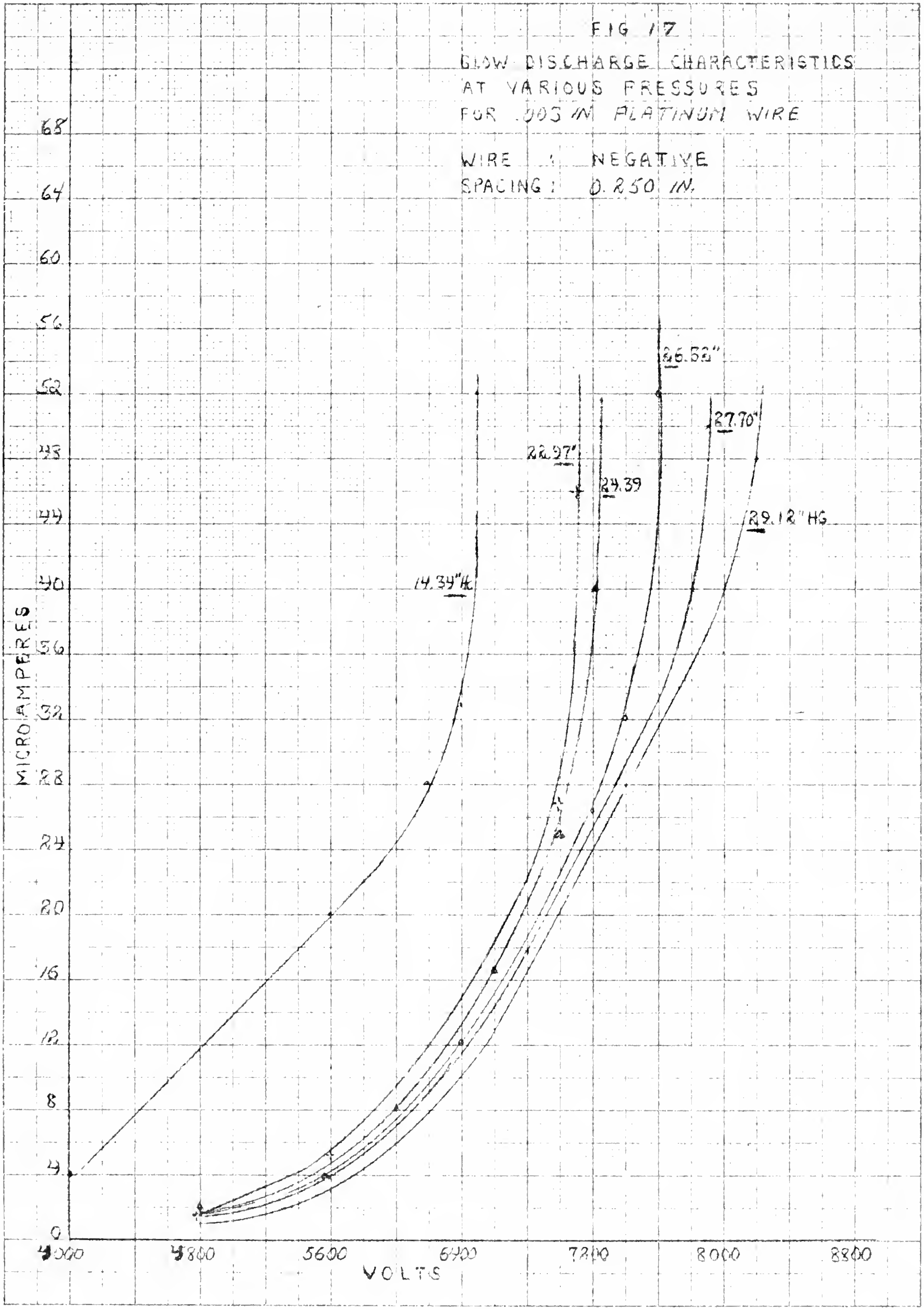


FIG 17
GLOW DISCHARGE CHARACTERISTICS
AT VARIOUS PRESSURES
FOR .005 IN PLATINUM WIRE
WIRE : NEGATIVE
SPACING: 0.250 IN.
MICROAMPERES
VOLTS
14.34" Hg
22.97"
24.39
26.52"
27.70"
29.12" HG

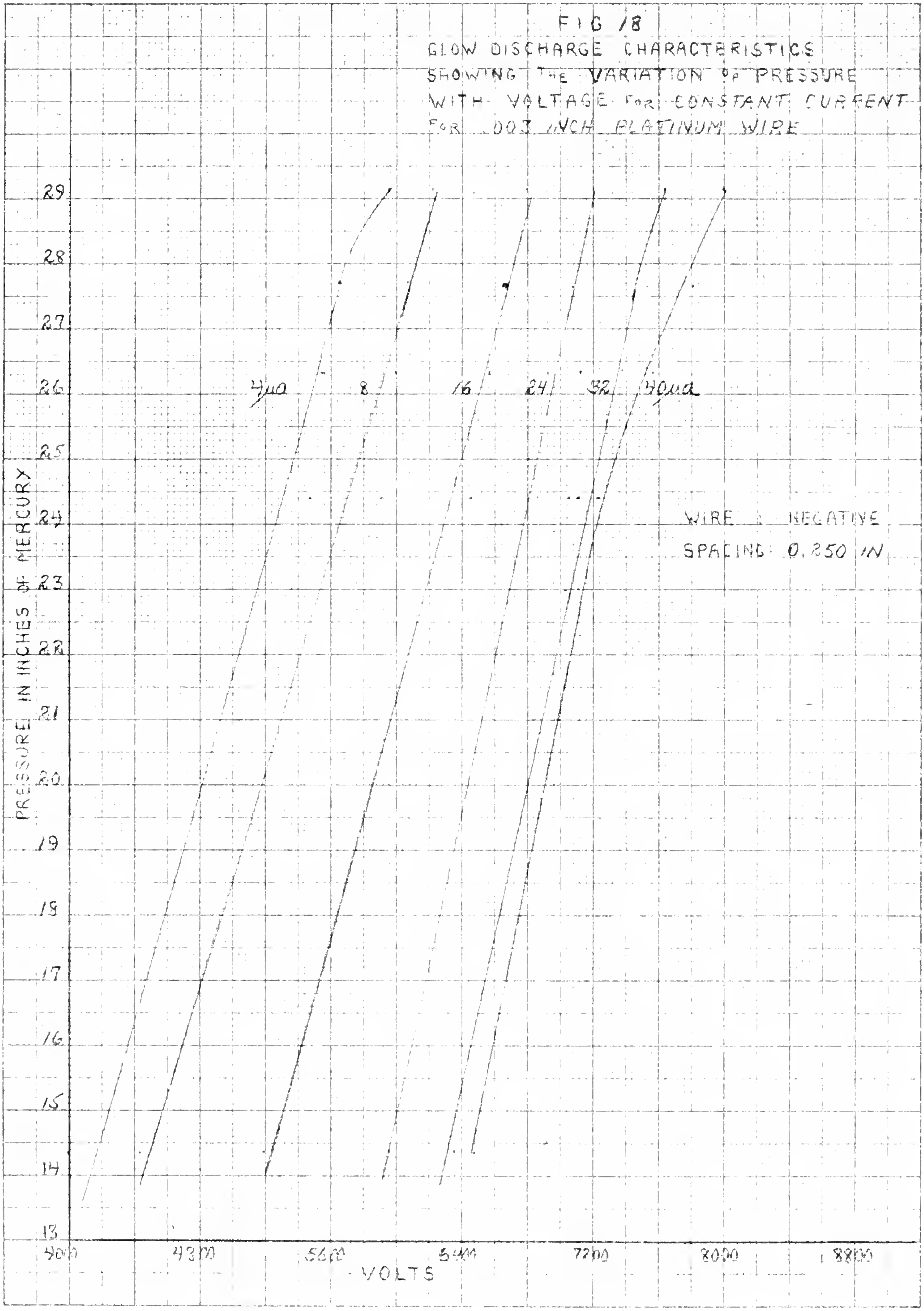


FIG 18
GLOW DISCHARGE CHARACTERISTICS
SHOWING THE VARIATION OF PRESSURE
WITH VALTAGE FOR CONSTANT CURRENT
FOR .003 INCH PLATINUM WIRE
4μa
8
16
24
32
40μa
WIRE : NEGATIVE
SPACING: 0.250 IN
PRESSURE IN INCHES OF MERCURY
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
VOLTS
4300
5600
7200
8000
8800

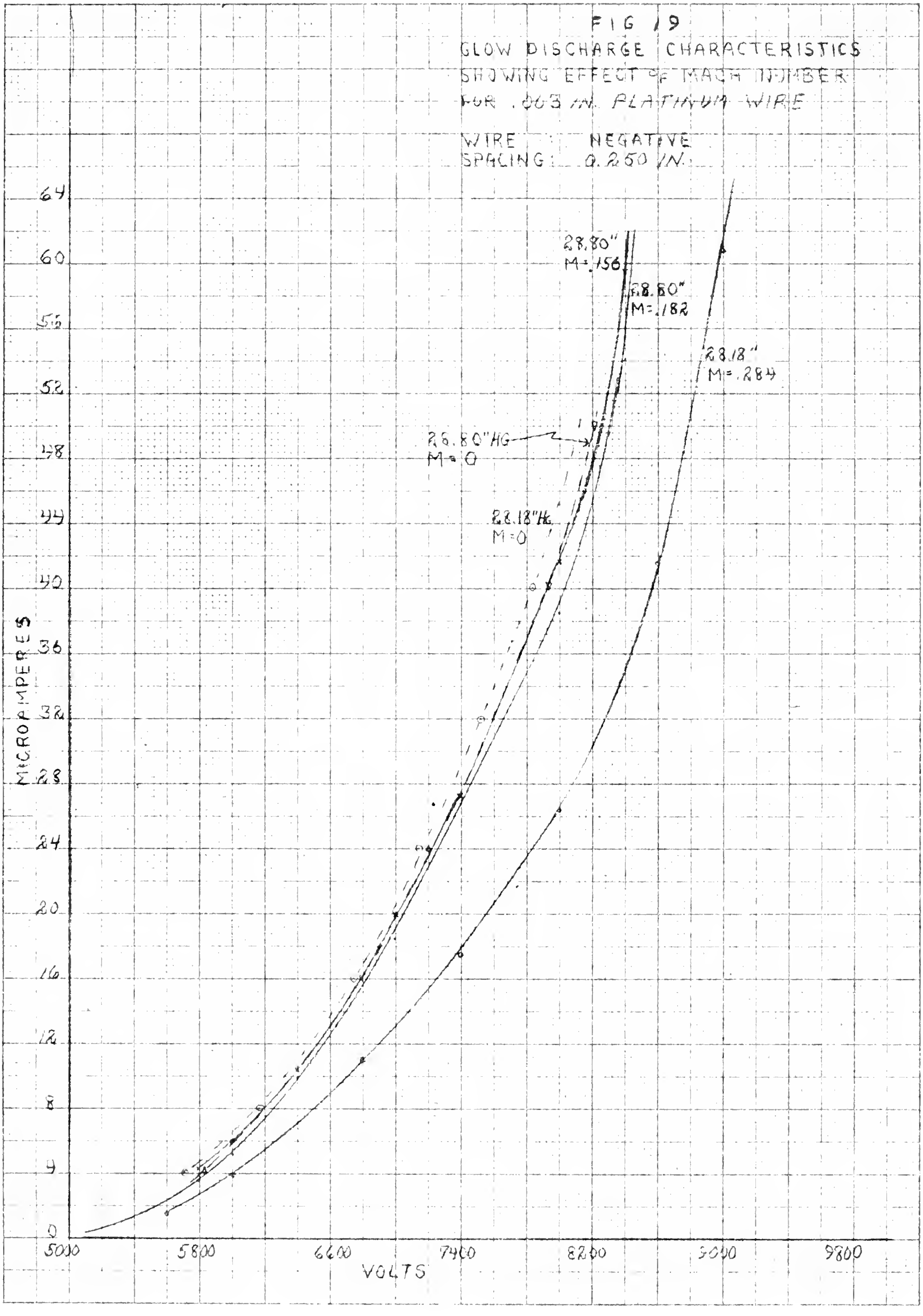


FIG 19
GLOW DISCHARGE CHARACTERISTICS
SHOWING EFFECT OF MACH NUMBER
FOR .003 IN. PLATINUM WIRE
WIRE : NEGATIVE
SPACING : 0.250 IN.
28.80"
M=.156
28.80"
M=.182
28.18"
M=.284
28.80" HG
M=0
28.18" HG
M=0
MICROAMPERES
VOLTS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
5000
5800
6600
7400
8200
9000
9800

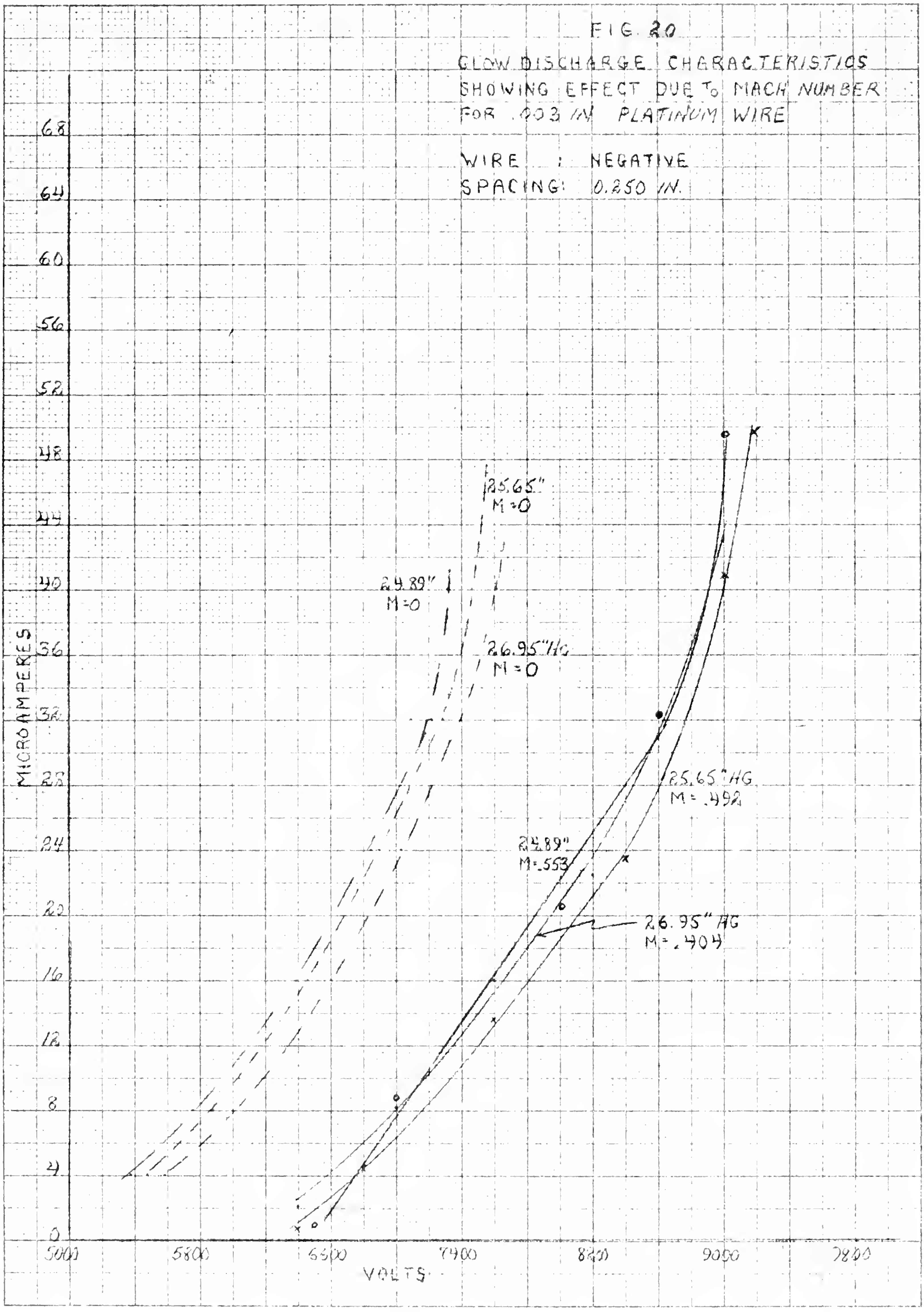


FIG. 20
GLOW DISCHARGE CHARACTERISTICS
SHOWING EFFECT DUE TO MACH NUMBER
FOR .003 IN. PLATINUM WIRE
WIRE : NEGATIVE
SPACING: 0.250 IN.
MICROAMPERES
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
VOLTS
5000
5800
6600
7400
8200
9000
9800
25.65"
M=0
24.89"
M=0
26.95" HG
M=0
25.65" HG
M=.492
24.89"
M=.553
26.95" HG
M=.404

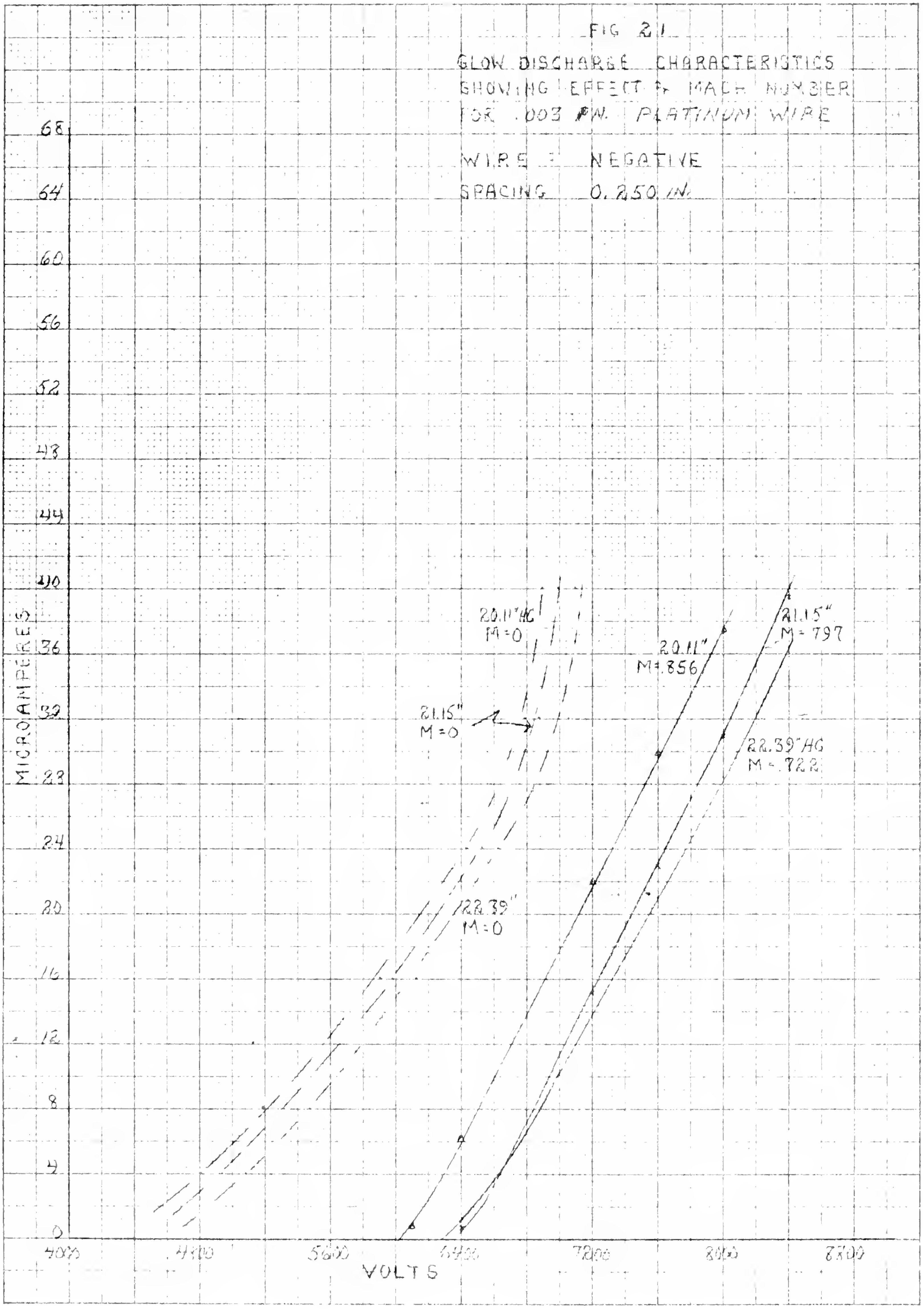


FIG 21
GLOW DISCHARGE CHARACTERISTICS
SHOWING EFFECT OF MACH NUMBER
FOR .003 IN. PLATINUM WIRE
WIRE : NEGATIVE
SPACING 0.250 IN.
MICROAMPERES
VOLTS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
4000
4800
5600
6400
7200
8000
8800
20.11" HG
M=0
21.15"
M=0
22.39"
M=0
20.11"
M=.856
21.15"
M=.797
22.39" HG
M=.722

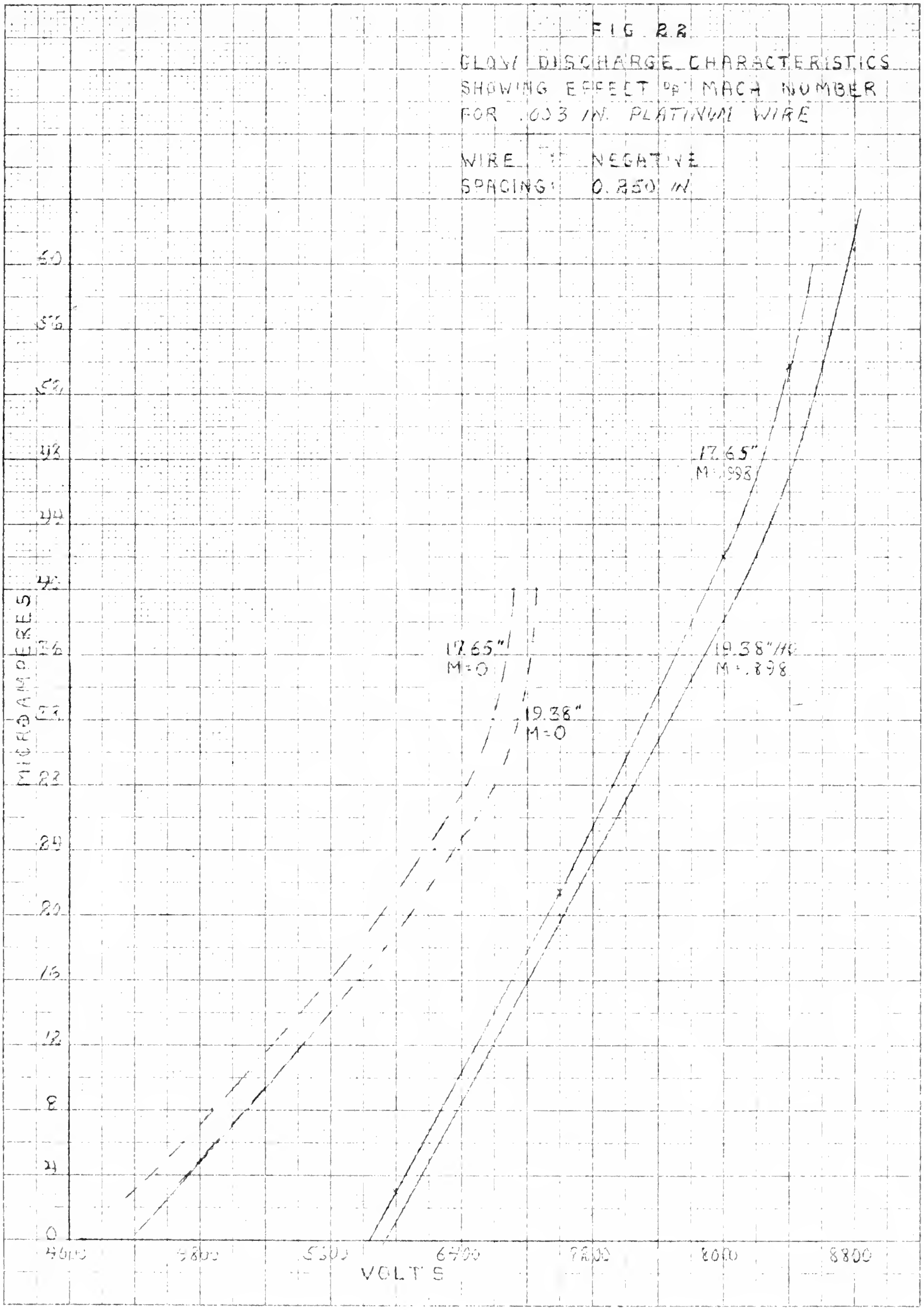


FIG 2.2
GLOW DISCHARGE CHARACTERISTICS
SHOWING EFFECT OF MACH NUMBER
FOR .003 IN. PLATINUM WIRE
WIRE NEGATIVE
SPACING: 0.250 IN.
17.65"
M=.898
17.65"
M=0
19.38"
M=0
19.38"
M=.898
MICROAMPERES
VOLTS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
4000
4800
5600
6400
7200
8000
8800

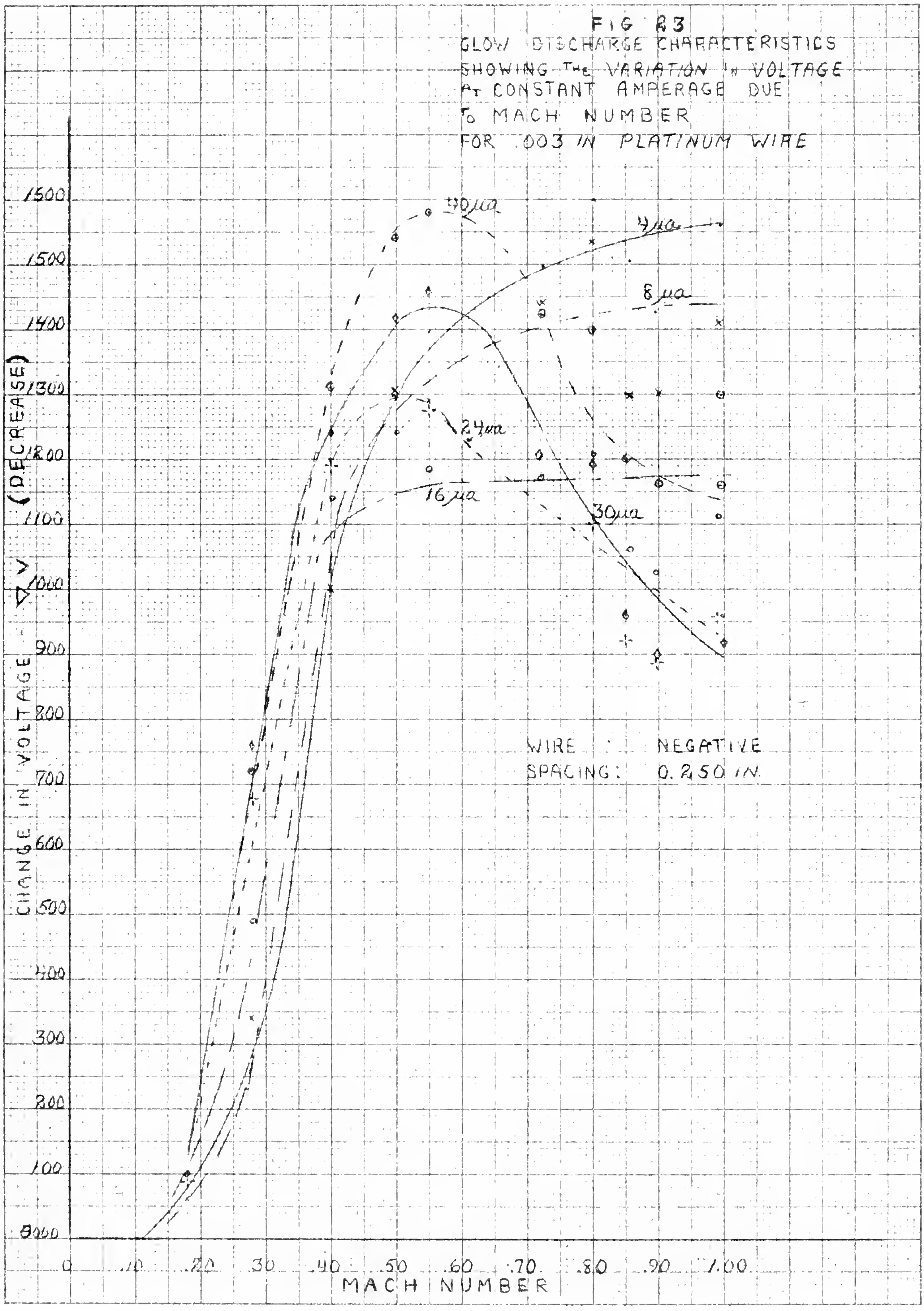


FIG 23
GLOW DISCHARGE CHARACTERISTICS
SHOWING THE VARIATION IN VOLTAGE
AT CONSTANT AMPERAGE DUE
TO MACH NUMBER
FOR .003 IN PLATINUM WIRE
WIRE : NEGATIVE
SPACING: 0.250 IN.
CHANGE IN VOLTAGE ΔV (DECREASE)
MACH NUMBER
4 μa
8 μa
16 μa
24 μa
30 μa
40 μa

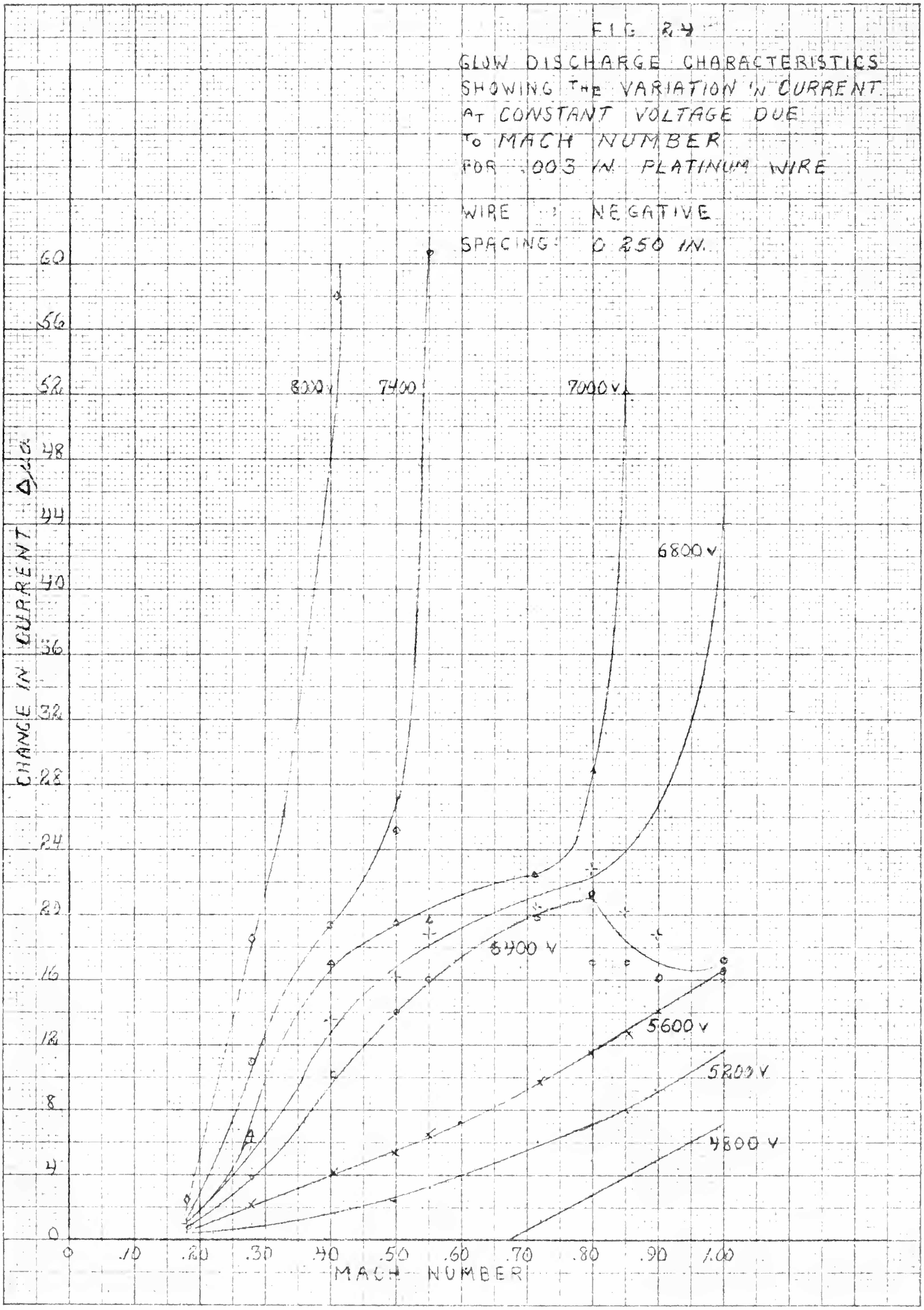


FIG. 24
GLOW DISCHARGE CHARACTERISTICS
SHOWING THE VARIATION IN CURRENT
AT CONSTANT VOLTAGE DUE
TO MACH NUMBER
FOR .003 IN. PLATINUM WIRE
WIRE : NEGATIVE
SPACING: 0.250 IN.
8000 V
7400
7000 V
6800 V
6400 V
5600 V
5200 V
4800 V
CHANGE IN CURRENT Δμa
MACH NUMBER
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60